

Physics in Perspective

Recommendations and Program Emphases

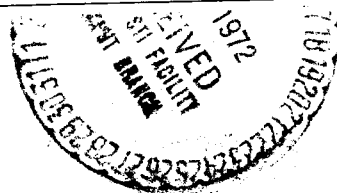
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NATIONAL ACADEMY OF SCIENCES

Physics in Perspective

Recommendations
and
Program Emphases

Physics Survey Committee
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1972

NOTICE: The study reported herein was undertaken under the aegis of the Committee on Science and Public Policy (COSPUP) of the National Academy of Sciences–National Research Council, with the express approval of the Governing Board of the National Research Council.

Responsibility for all aspects of this report rests with the Physics Survey Committee, to whom sincere appreciation is here expressed.

The report has not been submitted for approval to the Academy membership or to the Council but, in accordance with Academy procedures, has been reviewed and approved by the Committee on Science and Public Policy. It is being distributed, following this review, with the approval of the President of the Academy.

Preface

This report is excerpted from a much more extensive volume entitled *Physics in Perspective*, Volume I, the final report of the Physics Survey Committee. It is being made available in this form in order to provide more convenient access to the Committee's major recommendations and to its approach to the establishment of scientific priorities and program emphases.

The Physics Survey Committee was appointed by the President of the National Academy of Sciences in mid-1969 and charged with an examination of the status, opportunities, and problems of physics in the United States. The Committee has interpreted this charge broadly, and, in addition to its study of physics as such, it has attempted to place physics in perspective in U.S. society. It has evolved an approach to the establishment of priorities and program emphases that may have wider potential utilization; it has carried out detailed studies on education in physics and physics in education, on the production and utilization of physics manpower, on the dissemination and consolidation of physics information. Early in its activities the Survey Committee appointed some sixteen Panels charged with detailed examinations of different areas and aspects of physics. More than 200 active members of the U.S. physics community have participated in the Survey. Appendix B lists these participants and their affiliations.

Although the Survey has focused on problems of particular importance to the physics community, it has been clear that many of these

problems are much more general, affecting all of science. While the statistical data and the discussions throughout this report are rooted in physics, it is the Committee's hope that its conclusions and recommendations may be relevant in this broader context. Throughout its Survey the Committee has been reminded repeatedly of the very great unity, not only of physics itself, but also of all of science. This unity is all too often forgotten or ignored.

By its very nature a Survey Committee explores many alternatives and options in developing its report. It must be emphasized that the fact that a given one of these does not appear explicitly in the report does not imply that it has not been examined or considered.

In *Physics in Perspective* the Committee presents a status report on both the core areas of physics and those interface areas where physics has major interactions with other sciences. The most striking aspect of the entire survey has been the renewed discovery of the overall power and vitality of U.S. physics; this is a tribute to the generous support that it has received from the U.S. public over the past two decades.

But this strength is in danger. Throughout its report, the Committee has addressed itself to the sources of this danger and to the changes that it believes necessary if U.S. physics is to retain a leadership role in international science. Included herein, without change, is Chapter 2 of the Committee's report, Volume I, which brings together its major recommendations addressed to one or more of three audiences, the federal government and support agencies, the physics community, and the U.S. educational community, including its precollege as well as its undergraduate and graduate sectors. The supporting documentation and discussion for these recommendations are found throughout the Committee report and throughout the reports of the various panels that appear in *Physics in Perspective*, Volume II.

As a major part of its activity the Committee has addressed the difficult questions involved in any establishment of scientific priorities or program emphases. In its report (Volume I, Chapter 5) it presents a rather detailed discussion of the various approaches to these questions that have been discussed in the past. On the basis of these studies it has evolved an approach based on the "jury rating" application of certain criteria to the program elements of a subfield and has tested this approach on the core subfields of physics. Included herein is a condensed version of this Chapter 5, together with an Appendix from Chapter 4, of Volume I, which present the program elements involved and the Committee's rating of them. It again must be emphasized that the Committee views its ratings as representing only a first approximation to what it hopes will be a continuing process through which its approach and criteria can be improved and refined.

Chapter 5 of the Committee report, and the condensed version included here, also address the question of a national support level for the physics enterprise. In contrast to previous studies, an attempt has been made to provide a wide range of contingency alternatives such that whatever the level of support that may become available for physics in the competition for the available national resources, it may be used with maximum effectiveness to maintain the health and vitality of the national program.

Considered by themselves, the very limited excerpts from the Survey Committee report included here would give a grossly unbalanced view of the Committee's total effort. While presented for convenience in the present format, they must be understood within the context of the overall report.

For this reason Appendix A presents the Contents of Volume I. In addition, Appendix C reproduces the charge that the Committee addressed to its subfield Panels, thus providing an indication of the scope and substance of the panel reports prepared in response to it.

The Survey Committee has acted under the aegis of the National Academy of Sciences Committee on Science and Public Policy. Its work has been supported equally by the Atomic Energy Commission, the Department of Defense, the National Aeronautics and Space Administration, and the National Science Foundation; it has also received important support from the American Physical Society and from the American Institute of Physics.

The Committee cannot hope to acknowledge in detail all the assistance that it has received from many persons throughout the country during the course of this Survey. It would be remiss indeed, however, if it did not especially recognize the work of Miss Beatrice Bretzfield who has acted as secretary to the Physics Survey at the National Academy of Sciences since 1970 and of Miss Mary Anne Thomson, my administrative assistant at Yale.

March 17, 1972

D. Allan Bromley, *Chairman*
Physics Survey Committee

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1. Recommendations

INTRODUCTION

Science is knowing, and the most lasting and universal things that man knows about nature make up physics. As man gains more knowledge, what would have appeared complicated or capricious can be seen as essentially simple and, in a deep sense, orderly. To understand how things work is to see how, within environmental constraints and the limitations of wisdom, better to accommodate nature to man and man to nature.

For more than 25 years physics in the United States has set the style and pace of world-wide activity in this discipline. The major thrust of this Report is based on the belief that the interests of both the nation and this science will continue to be served best by the maintenance of physics as a vigorous enterprise at or near the frontiers of activity in each of its various branches. Such an objective is consistent with the vital role that physics plays in society, the unity of science, the importance that pre-eminence in science implies for the nation, and the expressed intent of both the executive and legislative branches of the U.S. Government.

The achievement of this objective in the face of changing national goals will require both making the most effective use of present resources and finding new sources of support for physics. Some of the difficult choices that may lie ahead, together with their probable consequences, are detailed in Chapter 5 of this Report and form the basis for the recommendations that follow. These recommendations are addressed to the community of physicists, which holds the responsibility for utilizing existing resources as

wisely as possible, and to the federal government from which additional support must be sought. They are augmented by the conclusions and findings presented in Chapter 14. Each has been cross-referenced to the chapter, or chapters, of the Report upon which it is based and to the specific audience to which it is addressed. More specific recommendations are to be found throughout the Report and in the panel reports in Volume II with the discussion that supports them.

Throughout the Report, and in many of the recommendations that follow in this chapter, we necessarily have addressed problems that are not unique to physics but common to all the sciences. Our discussions and recommendations relate almost entirely to the physics aspects of these more general problems and must be understood in this context as a contribution from one of the sciences to what must be, in many cases, much broader considerations.

SOURCES OF SUPPORT

Let there be no misunderstanding. Even with the most judicious use of existing resources, this nation cannot continue as a leading contributor to world physics without support greater than is now available. This objective faces the hard facts of changing national goals. Three of the four federal agencies that currently are responsible for more than 90 percent of the federal support of U.S. physics—the Atomic Energy Commission (AEC), Department of Defense (DOD), and National Aeronautics and Space Administration (NASA)—continue to suffer reduced funding, especially for their fundamental research programs; only the National Science Foundation (NSF) has experienced budget increases, and these have been largely offset by the transfer of basic research projects from other agencies and by the diversion of funding to more technologically oriented projects. In general the federal component of support is by far the largest and consequently commands greatest attention. To satisfy the new national priorities and make possible the achievement of the stated objectives of many of the new federal agencies, it will be necessary both to maintain and expand the research programs of the agencies that presently support physics and to develop other appropriate sources of funding for physics within the federal government.

RECOMMENDATIONS

FEDERAL GOVERNMENT

—Support Agencies

*Chapter 5
Chapter 14*

1. The federal agencies that have a long-term dependence on physics (the Atomic Energy Commission, Department of Defense, and National Aeronautics and Space Administration) should expand their support to a level more nearly commensurate with their stated needs. A strong reversal of the present downward trend in the support of basic science components of their programs is required to ensure the long-range capabilities of these agencies to fulfill their responsibilities.

FEDERAL GOVERNMENT

—Support Agencies

*Chapter 10
Chapter 14*

2. All federal agencies with missions that rely to some extent on basic physics should accept the support of physics research as a direct responsibility. These agencies include, among others, the National Institutes of Health, Department of Transportation, Department of Housing and Urban Development, Department of the Interior, Environmental Protection Agency, and Department of Commerce. The Office of Science and Technology should work with these agencies to develop general guidelines for such support. A 100:10:1 ratio, corresponding to the value of the high-technology product, the support of the related development, and the support of the underlying basic research, has characterized some mission-oriented federal agency and industrial programs in the past. The new agencies should strive for such a ratio in the allocation of their resources. If the side effects as well as the major thrust of each new development are to be understood and steps taken to mitigate or avoid possible undesirable consequences, it will be necessary in the

RECOMMENDATIONS

future to continue research as an integral part of the development process. This added requirement will inevitably increase the fractional research cost for new developments.

FEDERAL GOVERNMENT

—The Congress
—Atomic Energy
Commission

Chapter 10
Chapter 14

3. The recent addition to Section 31 of Paragraph (6) of the Atomic Energy Act as well as the revision of Sentence 1, Section 33, which now give the Atomic Energy Commission a general responsibility for research on energy, should be interpreted as encouraging support of those areas of basic research in physics that underlie this broadened responsibility of the Commission. To reflect the seriousness of the energy problems of the United States and the world, research appropriations of this agency should be increased substantially to permit vigorous attack on all aspects of research into energy generation and transmission. (See also page 34.)

FEDERAL GOVERNMENT

—The Congress
—Atomic Energy
Commission

Chapter 10
Chapter 14

4. In view of the outstanding success with which the U.S. Atomic Energy Commission has developed and supported a broad program of fundamental physics research, both in the past and at present, the Atomic Energy Commission should seek the necessary support—and the appropriations to this agency should be correspondingly increased—to enable it to maintain and expand its support of basic physics research programs in *both* the universities and the national laboratories.

FEDERAL GOVERNMENT

—Support
Agencies
—National Science
Foundation

Chapter 10
Chapter 14

5. In accordance with its primary responsibility for federal support of basic science, the National Science Foundation should seek to maintain the integrity and balance of the national physics program through selective emphasis on those segments of basic physics that have less obvious relevance to the missions of other federal agencies supporting physics research. Balance in the national physics enterprise should take priority over balance of the National Science Foundation physics program itself. To function adequately in this role the national support in basic physics now provided by the National Science Foundation should roughly double, and appropriations to this agency should be increased for this purpose. This increase should not be at the expense of the ongoing programs of the mission-oriented agencies.

PHYSICS COMMUNITY

—Nonacademic

Chapter 4
Chapter 7

6. In certain areas of basic physics industrial support is comparable with that from federal sources. It is desirable that this industrial support be maintained or increased to reflect the probable increased relevance of such knowledge to industry in the future, in relation to both productivity and the increasing need for foresighted technology assessment prior to the marketing of new products. Productivity will be of rapidly growing importance in maintaining the international competitiveness of U.S. industry over a broad range of product sectors.

STABILIZATION OF SUPPORT

As in any enterprise involving long-range goals, specialized facilities, and highly trained people, a degree of stabilization and continuity in the support of physics is essential to minimize the dislocation and waste of opportunity and training that all too frequently follow sharp changes and fluctuations in support. The consequences of the abrupt 1967 change in the rate of growth of U.S. physics support provide an instructive example and emphasize the need for developing and implementing long-range projections.

At the heart of the stability problem is the fact that the funding cycle has been an annual one, while the cycle for an experimental program, the completion of a graduate program of study, or the development of new research concepts to the stage at which they are widely used is more typically three to five years—if not longer. Many of the consequences of uncertainty could be removed if it were possible for funding agencies to provide investigators with reasonable assurances of support over this longer period. Certain agencies have attempted to establish their support of physics on such a forward-funding basis. Introduced some years ago during a period of increasing support, forward funding was rejected by most physicists because they felt that it would limit the flexibility and growth potential of their research programs. In the present period of more restricted funding, the advantages of forward funding have become much more widely appreciated and sought after. Unfortunately, however, this funding mechanism was an early casualty of the increasing pressure on agency budgets.

It should be emphasized that forward funding as such does not imply increased support levels. If the appropriations for a given fiscal year can be increased adequately to permit agencies to provide assurance of support for a portion of their programs for three to five years in advance, greatly increased stability can be obtained without increased treasury withdrawals for any given year. The annual cash flow would not be changed by such a procedural change, yet the return to science and the nation could be great. However, it will be important to avoid loss of flexibility, with the resultant inability to respond rapidly to new opportunities and needs; an appropriate balance between stability and flexibility might be achieved initially if one third of the program support were provided on a forward-funding basis.

RECOMMENDATION

FEDERAL GOVERNMENT

- Support Agencies
- Office of Management and Budget
- Office of Science and Technology

Chapter 6
Chapter 14

7. The federal agencies supporting physics should seek an increase in their appropriations in fiscal year 1974 and any necessary authority such that approximately one third of their physics projects could be assured support for a three- to five-year period. This particular incremental appropriation should be carefully supervised by the Office of Management and Budget to assure that it is used only as needed for the purposes of stabilization and not for an increase in program expenditures. It would imply that for those projects supported under the forward-funding programs, planning would always cover a minimum of three years.

ALLOCATION OF SUPPORT

One of the difficult decisions that must be faced in allocating available support involves the balance between two important national goals: the maintenance and advancement of the most innovative and significant science and the distribution of the available support to as many promising individuals and institutions as possible. When support is level or decreasing, these goals frequently are competitive and the choices are especially difficult to make.

The support of the highest quality activity and most promising people has long been a feature of the U.S. funding pattern; under conditions of limited funding this feature takes on increasing importance.

RECOMMENDATIONS

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| <p>FEDERAL
GOVERNMENT
—Support
Agencies
<i>Chapter 5</i></p> | <p>8. Under current and foreseeable economic constraints it is not possible to support adequately all those individuals and research groups identified as having excellent research ideas and high research potential as judged by federal agency review procedures and peer evaluations. In decisions on the allocation of funds, therefore, preference must increasingly be given to maintaining the position of individuals and groups who are at, or very near, the forefront of world activity in their subfields, consistent with maintenance of balance in the overall national program of physics.</p> |
| <p>FEDERAL
GOVERNMENT
—Support Agencies
<i>Chapter 5</i></p> | <p>9. Under conditions of limited support, programs should be terminated and facilities should be closed in preference to continued operation of all under marginal conditions.</p> |
| <p>FEDERAL
GOVERNMENT
—Support
Agencies
<i>Chapter 5</i></p> | <p>10. The construction of new facilities and the initiation of new programs should be restricted to situations in which clearly defined new needs or opportunities exist; under conditions of limited funding, programs and facilities justified primarily on the basis of geographical or institutional equity should be deferred. At the same time it must be emphasized that failure to respond to new needs and opportunities, when a clear consensus regarding them exists in any scientific field, can have an unusually detrimental impact on the overall progress of that field.</p> |
| <p>PHYSICS
COMMUNITY
—Academic
<i>Chapter 11</i>
<i>Chapter 14</i></p> | <p>11. While physics departments should continue to give students as wide a choice of fields of specialization as feasible, they should not support or initiate programs in areas of physics simply to have activity in all its major subfields. They should concentrate on those areas in which they can meet or exceed the critical level of activity required for high-</p> |

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quality work. Significant progress has already been made in the physics community in evolving regional cooperative arrangements to utilize most effectively particular strengths of the participating departments. These cooperative arrangements must be pursued with even greater vigor in the future.

PHYSICS AND NATIONAL GOALS

Limitations on man's ability to fulfill human needs often have technical components that can be removed only through research and development. Therefore, many industries and many federal agencies, such as the DOD, NASA, AEC, National Institutes of Health, and Department of Agriculture, invest heavily in research and development. However, some large industries and a number of federal agencies support little or no research and development.

Transportation, housing, and environmental quality recently have been designated national problem areas, and large federal agencies have been established to deal with them. To realize their potential for national service it is important for these new agencies to find ways to bring science fully to bear on the achievement of their missions.

Environmental monitoring provides an example of a problem area in which physics has an immediate and important role. The contaminants of greatest significance are frequently present in the natural environment at concentration levels so low that they elude detection with conventional monitoring instrumentation, yet the long-term consequences of their presence could be serious. Fundamental to any effective program of environmental improvement or control is the ability to detect these contaminants accurately with reliable and often portable instrumentation. The physics community has already responded effectively with a whole range of new ultrasensitive monitoring devices, but much remains to be done.

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FEDERAL GOVERNMENT

—Support Agencies

Chapter 7

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Chapter 14

12. The Department of Transportation, Department of Housing and Urban Development, and Environmental Protection Agency, as well as other agencies, should be encouraged by the Congress, the Office of Science and Technology, the Office of Management and Budget, and the scientific community—through legislation, directed funding, and proposal pressure, respectively—to undertake and support substantial research and development programs in physics relevant to their missions, including the basic research that contributes to their technical capability.

By making physicists partners in the enterprise several benefits will accrue to both the agencies and the national scientific and technical effort. First will be the advantages of a plurality of decision centers and a consequent diversity of criteria and viewpoints. This situation is healthy for science itself and also ensures an agency influence on the direction of evolution of the subdisciplines likely to be of particular significance to the agency in the future. Second, the association of both in-house and external scientists with the mission of an agency will assist it in the identification and appraisal of scientific discoveries made elsewhere in terms of their potential applicability to agency problems. Third, this association will help the agency in recruiting scientists who might later move into the more

applied problem areas of the agency, or identify new significant areas of basic research deriving from the technology of particular concern to the agency. In this way agency support of basic and long-range applied research can serve to sensitize portions of the scientific community and the educational system to particular societal problems that are the responsibility of the agency. During the 1950's and 1960's the DOD played such a role. It was beneficial to both defense technology and the development of science, but, because defense support assumed a very large relative role, particularly in physics and engineering, some imbalance of effort may have resulted. Today national priorities are changing, and physics has much to contribute to the solution of the newly emerging problems, but a serious effort is required to discover and establish the appropriate links between physics and these new areas. Relevance is not always obvious at first, and its discovery requires serious intellectual effort from both scientists and potential users of science.

PHYSICS AND THE NATIONAL ECONOMY

The relationship of technology to a healthy economy and a high standard of living has received much study. Advanced technology is also widely regarded as playing a crucial role in maintaining U.S. leadership in international trade as is discussed in Chapter 7.

Although a direct connection between the health of a nation's scientific enterprise and its economic strength may be difficult, if not impossible, to establish unambiguously, there is growing evidence to suggest that economic strength is linked not only to science itself but also to the scientifically trained manpower that flows into industry. In any steps taken by the federal government to improve the U.S. economy, certain measures relating particularly to the scientific aspects appear vitally important.

Recent developments have created serious demoralization in the scientific and technological community, largely because of the coincidence of three events. First, the financial crisis of the universities, cutbacks and policy changes in federal support of academic science, and rapid phase-out of student aid programs have combined to reduce abruptly the demand for new science faculty. Second, after 20 years of uninterrupted growth relative to manufacturing output, industrially financed research and development have been declining because of the national economic recession, and industrial basic research has been particularly seriously affected. Third, federal cutbacks of research and development programs in aerospace and electronics, which have been going on since 1965, have produced serious employment dislocations among technical people, accentuated in certain geographical areas. These three trends reinforcing each other after a long period of scientific and technological prosperity have had a truly devastating effect on the physics profession. Yet these trends have come at a time of growing realization that the nation faces serious challenges in the fields of energy, transportation, and environmental protection and management and a breakdown in the delivery of several important public services such as education, health care, social welfare, and other urban services. All of these challenges have important scientific and technological content.

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FEDERAL GOVERNMENT *Chapter 7*

13. The federal government should take immediate steps to develop new mechanisms and incentives for the support of substantially expanded industrial basic and applied research programs. The support by industry of the basic science that can contribute to its products and services—both in-house research and cooperative efforts with universities and governmental laboratories—should be strongly encouraged as one approach to strengthening the base of the nation's industrial economy. Means should be sought to stimulate support of basic research by associations of all member companies in an industry. The benefit to the nation's industry as a whole, resulting from any typical piece of industrial

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research, can usually be shown to be considerably greater than the benefit received by the particular industry that supported this research.

**SCIENTIFIC
COMMUNITY
FEDERAL
GOVERNMENT**

**-Support
Agencies**

*Chapter 7
Chapter 14*

14. During the last decade there has been rapid growth in economic research on computing rates of return on investments in the innovation process in both industry and agriculture. Nevertheless this field of research is still in a very rudimentary state, and very few definitive conclusions are possible. Furthermore, there is almost no adequate understanding of the interrelationships or relative contributions of the various components of the total innovation process ranging from basic research through development to production and marketing. Greater collaboration is strongly urged among natural scientists, economists, and sociologists in developing a more coherent and usable theory of the innovation process, and we urge federal agencies such as the Department of Commerce and the National Science Foundation to identify and support worthwhile projects in this area. At the same time great caution should be exercised against drawing practical policy conclusions from such studies prematurely.

PUBLIC AWARENESS OF SCIENCE

Science is generally regarded as a vital element of western culture. Physicists, and indeed all scientists, owe it to themselves and to society to develop increased public awareness of this relationship. Yet, despite much lip service, little use has been made of public information media to fulfill this obligation to the public, and the potential of the professional and scientific societies for creative activity in this area also has been too little utilized. The time has come for individual physicists to demonstrate in more tangible fashion their support for oft-repeated statements of principle in this area. The BBC second channel, for example, presents an hour-long scientific documentary for each of 40 weeks each year; competing in prime time, these documentaries have an audited response that has reached five million persons, or some 11 percent of the British population. In contrast, U.S. television coverage of science is in a sorry state.

RECOMMENDATIONS

PHYSICS COMMUNITY

Chapter 11

15. All physicists, whatever the nature of their professional activity, should encourage those members of the physics profession with talent for such activity to devote a significant fraction of the time and resources available to them to introduce as many of their fellow citizens as possible—children and adults alike—to the pleasures and satisfaction that come from greater understanding of natural phenomena through application of the concepts and laws, as well as the style and approaches, of physics. A small but increasing number of physicists have written books and articles presenting the activities in their field at a level accessible to an interested public. Very much more remains to be done.

PHYSICS COMMUNITY

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16. The member societies of the American Institute of Physics should assess each of their individual members not less than ten dollars per year to create a fund that would be used by the American Institute of physics as seed money, and with matching assistance from foundations and other private sources, to further the use of mass media for informing the public in an understandable and interesting fashion concerning physics and its role in contemporary society.

PHYSICS COMMUNITY

Chapter 11

17. Recognizing the dominant position that television now enjoys in reaching the U.S. public and the future potential of cable television in particular, the American Institute of Physics, with support such as that recommended above, should actively explore the presentation of a continuing series of television programs concerning physics. A joint venture with other major scientific societies such as the American Chemical Society should be considered in order to reach a critical size at the

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earliest possible time. The National Academy of Sciences should take the lead in bringing together the interested parties and in coordinating this effort.

PHYSICS COMMUNITY

—Nonacademic

Chapter 11

18. Industries and foundations should further develop channels and mechanisms for supporting the creative utilization of public communication media in areas of science. The U.S. Steel Foundation, for example, annually awards, through the American Institute of Physics, prizes for distinguished scientific journalism and scientific writing directed toward a broad public audience.

PHYSICS COMMUNITY

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19. Physicists should work actively to encourage and support science museums as effective approaches to furthering public awareness of science. Washington, Boston, Chicago, New York, and San Francisco are examples of major U.S. cities with established science museums that are used as centralized teaching resources for the entire urban communities they serve. The San Francisco Exploratorium concept, which makes possible greater interaction between visitors and the museum displays, marks an important advance in the effectiveness of such institutions; other possibilities exist and should be developed.

PHYSICS AND PRECOLLEGE EDUCATION

In a viable democracy it is essential that each participating citizen appreciate the scientific and technological bases of his society. Unless the general public can understand something of the world of science and appreciate the nature and goals of scientific activity, it will not be able to fit science and technology properly into its perspective of life. As that life becomes increasingly conditioned by the products of science and technology, diffidence and even apathy grow, ultimately having adverse effects on the nation's capacity to maintain leadership, whether it be moral, intellectual, or economic. The science education of the general public beginning in the earliest school years should be a matter of grave concern to the physics community.

Thy typical U.S. teacher, at both elementary and secondary levels, is not well equipped to guide his pupils in learning that science is more than a collection of facts to be memorized or techniques to be mastered but is instead an inquiry carried on by people who raise questions for which answers are unknown and who have gained confidence in their ability to reach conclusions, albeit tentative ones, through experiment and careful thought sharpened by the open criticism of others. At the same time science is that body of established fact that is the common heritage of all men.

This inability of most teachers to impart some understanding of the nature of science results largely from a science education that fails to give the potential teacher an adequate appreciation of either of its above aspects. Thus we recycle the attitudes that sustain widespread illiteracy about science and technology. There is a point of leverage in the cycle; all future teachers should receive increased exposure to science and appropriate mechanisms should be developed to this end. Physics departments and faculties in universities and colleges cannot afford to ignore the opportunity thus presented to initiate a long-term but sure approach to public understanding through education of the teachers who will provide the main point of contact between science and the average educated member of the public.

At the same time current indicators suggest that elementary and secondary school teaching is an oversubscribed employment market. These teachers typically acquire tenure after three years (as opposed to the seven years characteristic of college and university teachers). As a result only a relatively small fraction of the total number of U.S. school-teachers will be replaced in the near future. Consequently, changes in the education of new recruits to the teaching profession are not enough; the retraining and continuing education of the present teachers are essential and major components of any realistic effort to improve the quality of precollege education in the United States.

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PHYSICS COMMUNITY

—Academic

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20. Physics faculties in colleges and universities should acknowledge their clear responsibility for science education of the general public by developing and staffing courses, suitable for all the teachers of our young, that emphasize individual inquiry, contact with phenomena,

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and critical evaluation. Excellent models for these courses already can be found in the new elementary school science curricula to which physicists have made major contributions. Because such courses have merit for the nonscience student more generally, faculties of institutions not offering a degree program in education should involve themselves just as intensively in this effort as should those having direct responsibility for teacher preparation. Science is too vital a part of modern life to be taught only as a separate unit. More emphasis should be given to the importance of physics in other fields of endeavor.

PHYSICS COMMUNITY

—Academic

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21. U.S. colleges and universities should develop and make available to science majors, as well as recent graduates, the courses that would be required to enable them to meet state certification requirements for teaching in public schools. The justification, in principle, for appropriate methodology requirements is recognized. However, many excellent candidates are presently precluded from precollege teaching because of certification requirements that frequently emphasize methodology at the expense of content.

FEDERAL GOVERNMENT

—Office of
Education

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22. The Office of Education should encourage all state departments of education to work toward a uniform set of certification requirements with enhanced emphasis on content as opposed to methodology. Progress in this direction would serve to increase the pool from which scientifically talented and trained personnel might be attracted into precollege teaching.

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23. The physics community should expand its current involvement in local educational activities and should actively support and encourage those of its members with talents for, and interest in, the improvement of science teacher training and of the science content in precollege curricula. Cable television, with its greatly increased capability for educational use, should not be overlooked by physicists as a tool in their attempts at improving physics education at all levels.

PHYSICS COMMUNITY

—Academic

Chapter 11

24. Universities and colleges should make a particular effort to develop and make available to schoolteachers, in their local areas, courses designed to improve the level of their training in their various fields of academic specialization.

There is abundant evidence that practically all those who major in physics in college and go on to a PhD have taken at least one physics course in high school. Thus high school physics enrollment is a good indicator of the potential future supply of physics and, to some extent, engineering manpower. High school physics enrollments have been going

sharply downward for several years, as discussed in Chapter 12, and the decline may well become even sharper in view of the present employment situation for physicists. As a practical matter there is approximately an 11-year lead time in the production of PhD physicists; therefore, it is important to keep careful watch on the pool of high school physics students. Both the scientific community and the federal government must take active measures to alleviate the possible consequences of overreaction to present employment problems insofar as this results in decreased scientific exposure in precollege education.

RECOMMENDATION

PHYSICS
COMMUNITY
FEDERAL
GOVERNMENT
Chapter 12

25. The physics community and the federal government should monitor the potential pool of high school graduates from which future physicists are drawn. There is an urgent need to develop more sophisticated dynamic models of the manpower flows in physics that take into account the influence of economic factors on the supply of potential talent at all levels and the demand for physicists at the BS and PhD levels. The government and the physics community should move to counteract present tendencies to escalate formal educational qualifications for employment and give more publicity to the career opportunities, including teaching below the college level, that are available to BS and MS level physicists.

PHYSICS AND UNDERGRADUATE EDUCATION

The goal of physics is a deep understanding of nature economically reduced to a few broad principles. Therefore, it provides a foundation on which other sciences and engineering can build. But physics is also a vital part of human cultures, as Chapter 3 indicates. During the past decade U.S. colleges and universities have emphasized the professional aspects of undergraduate physics, frequently to the exclusion of courses directed toward nonscientists or nonphysicists. Frequently, too, this preprofessional bias has led to the exclusion from undergraduate curricula of courses in more applied subfields of physics such as optics, acoustics, and hydrodynamics.

RECOMMENDATIONS

PHYSICS COMMUNITY

—Academic

Chapter 11

26. Physics departments should place renewed emphasis on the teaching of physics to nonphysicists. To do so requires the development of curricula parallel to those designed for preprofessional majors. Much progress has already been made in this direction in recent years.

PHYSICS COMMUNITY

—Academic

Chapter 11

27. The physics community and physics departments should make a determined effort to regain the breadth and flexibility that have traditionally characterized education in physics. Accomplishing this objective will require a re-emphasis on many branches of classical physics in undergraduate and graduate curricula, stimulation of broader interests among students, and exposure to the opportunities and challenges presented outside the core areas of contemporary physics and other than those that academic teaching and research can offer.

FEDERAL GOVERNMENT

PHYSICS COMMUNITY

Chapter 12

28. As noted above, the federal government and the physics community should act to maintain a level of BS physics production adequate to the nation's needs. The number of BS degrees granted in physics should not be allowed to fall much below the present 5000 per year if a supply of manpower adequate to fulfill future teaching and research needs is to be maintained. Current trends suggest that unless vigorous corrective action is taken now the nation will experience yet another major oscillation wherein the supply of and need for trained physicists become grossly mismatched.

PHYSICS COMMUNITY

Chapter 11

29. The physics community, acting through the American Association of Physics Teachers, should prepare and publish objective descriptions of the curricula and the facilities available for the teaching of physics in all those institutions that now offer a stated undergraduate major in the

RECOMMENDATIONS

field. This measure will not only act to provide much needed information to secondary school graduates embarking on a career but also will foster upgrading or elimination of marginal programs. The American Institute of Physics currently publishes an annual Directory of Physics Departments. This Directory, however, is all too rarely accessible to undergraduates and is not designed to provide information adequate for an informed choice of graduate programs. Too many physics students, having invested one or more years in graduate programs, find themselves trapped in schools or programs with faculties and facilities inadequate to provide them with an education of high enough quality to enable them to realize their inherent potential for career growth.

30. Greater emphasis must be placed on regional cooperation wherein individual physics departments can specialize in their research activities to achieve "critical mass" while at the same time providing an adequately broad educational exposure to their students through cooperative utilization of faculty to teach advanced courses in their areas of specialization. A number of successful examples of such cooperation already exist in the physics community. The physics community should face the fact that faculty requirements for teaching and research have very frequently been mismatched. All too often such mismatches have been effectively hidden by funding from external sources. In many physics departments the numbers of undergraduate physics majors and physics graduate students simply do not justify a faculty of adequate size to mount research programs of critical mass in all the areas in which they currently pursue research.

PHYSICS COMMUNITY

—Academic

Chapter 11

GRADUATE EDUCATION IN PHYSICS

Traditionally graduate education in physics has involved a style of activity and a flexibility of approach that prepared students for a broad range of activities. Departments of physics in major institutions have a continuing responsibility to provide the best possible graduate education to those who want it and can profit from it. However, for at least the next few years it should be recognized that holders of advanced degrees in physics will less easily realize their aspirations, if these lie in the academic sphere, than in the 1960's. This rather abrupt shift in the market for physicists places an especially heavy responsibility on teaching faculties to provide realistic advice to their students concerning their projected career opportunities.

A number of current problems in graduate education in physics reflect the rapid growth of both faculties and facilities in the nation's physics departments during the 1960's. (See Chapter 12.) Although it is obvious that the quality of many of these departments improved markedly during this process, a fundamental instability was built into the academic system through the generally accepted practice of using federal grant and contract support to pay increasingly large fractions of the salaries of faculty members. Many departments used this mechanism to expand the size of their faculties, both tenured and nontenured, beyond the number that their institutions could afford to carry during periods of reduced funding of academic physics.

RECOMMENDATIONS

PHYSICS COMMUNITY

—Academic

Chapter 11
Chapter 12

31. Physics department faculties should devote particular attention to the counseling and guidance of students who wish to undertake graduate education in physics to ensure that their career choice is a well-considered one. This responsibility involves an honest and realistic appraisal of the faculty and facilities of the institution involved and of how their contributions to the educational needs of the student compare with those obtainable elsewhere. It also involves supplying students with realistic assessments of the job market and of their abilities to compete in it. Physics departments have an obligation to offer an education that provides maximum flexibility in adapting to career options.

PHYSICS COMMUNITY

—Academic

Chapter 14

32. University administrations should recognize their local responsibility for the maintenance of the viability of their scientific departments. In many fields, and especially in physics, dependence upon external support for research has become so great that fluctuations in that support can be disastrous, unless damped by local action. The present tendency to shift this responsibility to the federal government alone can have serious and unfortunate consequences as the current situation all too clearly indicates. In particular, university administrations should

RECOMMENDATIONS

exercise restraint in the establishment of new or expansion of old programs simply because of the apparent availability of federal or other external support. They should exercise equal restraint in terminating established and ongoing programs simply because of the disappearance of this same external support and, to a degree much greater than has recently been the case, should be prepared to devote institutional resources to the orderly readjustment of the many high-quality programs that have experienced drastic reductions in their external support. University departments and administrations should take steps to reduce their dependence on funding sources external to their institutions for the support of academic-year faculty salaries.

PHYSICS COMMUNITY

—Academic

Chapter 9
Chapter 14

33. Physics departments should abandon the idea that to achieve or maintain greatness they must maintain research activity simultaneously in all the major subfields of physics. Rather, under conditions of limited funding they should select those areas in which they have the faculty and facility resources to achieve or maintain excellence and, if necessary, sacrifice marginal programs to permit the development of those selected areas. Many of the established physics departments, indeed, have long ago made such hard decisions; if many of the other departments do not follow this example they risk mediocrity. Obviously such actions, at the same time, place a high premium on the development of local or regional cooperative arrangements among institutions whereby the specialized training and research facilities of each are available to all. Otherwise there is a real danger that graduate education can become even more specialized and inflexible than it frequently is now.

INTERDISCIPLINARY ACTIVITIES

Physics and physicists have significant contributions to make to the solution of major national problems, many, if not all, of which require concerted attack by a wide variety of disciplines. The attention these national problems have received recently has fostered the rapid development of interdisciplinary programs, majors, and departments in various U.S. colleges and universities. Although many of these activities are of high quality, great care is needed to prevent the programs, the teachers, and the taught from becoming divorced from the underlying disciplinary roots. The problem of the second and later generation in interdisciplinary areas requires particular attention. Although the first generation comes, necessarily, from well-established fields with clearly defined requirements and intellectual standards, there is a tendency, in response to the often broader spectrum of activities related to an interdisciplinary field, to substitute, in the training of second-generation students, a somewhat cursory or introductory exposure to many subjects for fundamental mastery of a few basic subjects.

RECOMMENDATIONS

PHYSICS COMMUNITY

—Academic

Chapter 11
Chapter 14

34. Since it is reasonable to assume that persons with a solid foundation in and open communication with a particular discipline can make the most significant contributions to interdisciplinary activities, colleges and universities should guard against proliferation of interdisciplinary degree-granting educational programs at the undergraduate level. Rather, they should concentrate on providing a strong grounding in the fundamental disciplines and use interdisciplinary programs to produce increased awareness of the application of these fundamentals.

PHYSICS COMMUNITY

—Academic

Chapter 11
Chapter 14

35. Universities should facilitate the study of interdisciplinary and interdepartmental problems at the graduate level and should be prepared to recognize imaginative and innovative contributions to the solution of such problems as equivalent to the traditional departmentally oriented dissertations in satisfaction of degree requirements. At the same time the intellectual standards of the participating disciplines should be clearly maintained in the graduate course work components of these degree requirements.

THE ROLE OF PHYSICISTS IN EDUCATIONAL AGENCIES

Scientists in the United States in general, and physicists in particular, have had little direct contact with the activities of the Office of Education of the Department of Health, Education, and Welfare. Consequently, they have had relatively little influence in the community of professional educators or the development of national policies affecting education. This situation also exists at state and local levels. The major interaction between scientists and the professional education groups has occurred through the Education Directorate of the NSF.

RECOMMENDATIONS

FEDERAL GOVERNMENT
—The Congress
Chapter 11

36. Legislation should be sought that would require the establishment, in the Office of Education, of advisory committees of scientists and educators for each of the major scientific fields including physics.

FEDERAL GOVERNMENT
—Office of Science and Technology
Chapter 11
Chapter 14

37. The Office of Science and Technology should take the initiative in ensuring that physicists and other scientists have access to the national educational policy levels through the above and other appropriate mechanisms.

ALLEVIATION OF SHORT-RANGE MANPOWER PROBLEMS

One of the most serious problems resulting from the abrupt change in the growth rate of physics in the United States is that of finding career opportunities for the young men and women who began their professional education during a period of expansion but now face a situation in which many of them will be unable to use more than a small part of their special training. Qualitative changes in physics department activities can alleviate some of the short-term aspects of this problem, albeit without really addressing its very serious long-range aspects. In the present difficulties the physics community may have to meet its responsibility to its recent graduates at the expense of at least a temporary reduction in the number of those entering the field. It is vastly preferable to exercise control at the beginning of the educational pipeline. (Chapters 6, 11, and 12 address the manpower problem in physics in greater detail.)

RECOMMENDATIONS

PHYSICS COMMUNITY

—Academic

Chapter 6
Chapter 11

38. Admission of graduate students primarily on the basis of their anticipated contribution to the undergraduate teaching process should be abolished. Indeed, under the present employment conditions, departments that have traditionally used large numbers of graduate students as teaching assistants should consider replacing many of them with postdoctoral instructors. All too frequently graduate education in physics, as indeed in all the sciences, has been looked on as a necessary by-product of the education of undergraduates, largely because graduate students have long provided a relatively inexpensive component of the undergraduate teaching staff. This problem has been a particularly severe one at some of the larger public universities under the pressures of burgeoning undergraduate enrollments.

PHYSICS COMMUNITY

—Academic

FEDERAL GOVERNMENT

—Support
Agencies

Chapter 6

39. Where feasible, physics departmental research groups should replace a significant fraction of their present graduate student complement with postdoctoral research associates. Evidence exists that such replacement is already in progress in many physics departments. Federal support agencies should also view postdoctoral positions supported by research grants with greater sympathy than has been the case in the past, even at the cost of supporting fewer graduate research assistants.

Both of these recommendations are intended to reduce temporarily the entering graduate student population and provide additional job opportunities for recent graduates. These measures offer no lasting solution to the current employment problem inasmuch as such positions are at best temporary, but they do provide a "holding period" for adjustment and for exploration of wider employment horizons.

Earlier, the support of excellence in allocating available funds for research was recommended. Yet, as discussed in this Report, the sharpest decrease (50 percent between 1969 and 1971) in the entering graduate student population in physics has occurred at the most distinguished physics departments in the nation. Thus, an increasing fraction of the young men and women of this country who are interested in physics are being educated in institutions with less than the best available faculties and facilities at a time when the highest quality institutions are operating far below capacity. This situation has been, in part, the result of a federal policy decision to phase out national fellowship and traineeship programs rapidly.

RECOMMENDATION

PHYSICS COMMUNITY

—Academic

Chapter 11
Chapter 14

40. The nation's most able physics departments have a responsibility to make their faculties and facilities available to as many well-qualified candidates as can properly be accommodated. They should resist pressures toward reduction of their entering graduate student populations because of the general national reduction in employment opportunities for MS and PhD graduates. New student-support methods must be developed to prevent a deterioration in the average quality of U.S. graduate education that this, and other, present trends portend.

One of the fundamental problems here is the natural desire of physics faculties in all colleges and universities to work with graduate research students. The problem is particularly severe in schools with marginal physics facilities and physics faculties of marginal quality and size that increasingly contribute a significant fraction of the total number of new PhD's each year. While attention is directed here to this problem as it affects physics, it is by no means unique to physics.

RECOMMENDATION

FEDERAL GOVERNMENT

—Support
Agencies

Chapter 11

41. To the extent that they can make funding available in competition with the needs of the nation's most able research groups (see Recommendation 8, page 7), federal agencies should develop, for at least the immediate future, research funding mechanisms and appropriate criteria that would permit selected physics faculty members in colleges or smaller universities to engage in research without training graduate students. This they might do either locally or as members of user groups at regional or national facilities or as part-time members of research teams at the major universities. The research support could include short-term postdoctoral staff. In recognition of the special character of this support, it would be hoped that colleges and universities involved would agree not to initiate doctoral training programs (or to admit new students to existing programs) in the corresponding areas of physics.

INSTRUMENTATION

One of the major areas of contact between physics research and society is through physics-derived instrumentation. Devices and concepts originating in physics research now play primary roles in medicine and industry and throughout all of technology and other science. And, indeed, the quality of physics research itself depends in no small measure on the quality of its instrumentation. For decades the United States has been a world leader in the commercialization of new instruments, and the instrument industry, though relatively small, has been an important source of favorable trade balance. Among the early casualties of reduced funding in major laboratories have been both instrumentation activities and instrumentation groups. Although the scientific groups in these laboratories, as discussed throughout this Report, continue to originate new ideas and concepts relating to instrumentation, their instrumentation activities have been markedly reduced because of budgetary pressures. At the same time the flow of new ideas and new devices from the dwindling instrumentation groups themselves, which have long been a steady and continuing source of innovation in instrumentation, has almost ceased.

Furthermore, with increasing pressures on budgets throughout the economy, the purchase rate for new instrumentation has decreased markedly, with research, engineering, and medical groups living on their instrumentation capital. Continuance of this trend can strangle the U.S. instrumentation industry, which remains as the source for innovation following the effective withdrawal of the university and national laboratories from this activity.

The short-range instrumentation economies now apparent throughout physics, and science more generally, can have the most serious long-range consequences in significantly weakening the U.S. instrumentation industry both nationally and internationally.

RECOMMENDATIONS

SCIENTIFIC COMMUNITY

*Chapter 4
Chapter 14*

42. The National Academy of Sciences and the National Academy of Engineering should jointly establish a committee to assess the needs of the U.S. instrumentation activity and the ways these might most effectively be met. The recent NSF summer study on instrumentation provided a start in this direction; however, it was limited in scope and was also limited to instrument procurement and even then to procurement of relatively low-cost instrumentation. The questions of instrumentation development and the procurement of major instrumentation require comprehensive analysis and assessment.

FEDERAL GOVERNMENT

*—Support
Agencies*

Chapter 14

43. The National Science Foundation, Atomic Energy Commission, and other agencies supporting physics research and development should seek funding specifically for support of instrumentation development and instrumentation development groups. The committee recommended in 42 above, working with agency representatives, should develop the

RECOMMENDATIONS

detailed criteria to be applied to those seeking support. In any program to support instrumentation development in universities and national laboratories, it is essential that mechanisms be included to ensure close and continuing interaction with active research groups; otherwise, the development activities can become sterile and instrumentation can be pursued for its own ends rather than as a support to research and development activities. It is recommended that instrumentation groups and activities be integral parts of the scientific departments or divisions of their host institutions.

CONSERVATION OF HELIUM RESOURCES

An adequate supply of helium is of crucial importance to any future implementation of superconducting technology—as in the transmission of electrical power or in new computer memory configuration, to give only two examples. Moreover, large components of contemporary physics research—in condensed matter, elementary particles, and nuclear physics—are entirely dependent on liquid helium to achieve adequately low working temperatures. While it may be argued that eventually superconducting systems may be found that can operate at the higher temperatures characteristic of liquid hydrogen, none has yet appeared.

In the meantime, although the United States holds a major fraction of the world helium supply in its natural gas wells, this irreplaceable resource is being squandered in alarming fashion. Current estimates suggest depletion of world reserves by the year 2000 or shortly thereafter.

During the past decade, pursuant to the Helium Act Amendments of 1960 (Public Law 86-777, 13 September 1960), the federal government has maintained a conservation program involving helium extraction from natural gas at the well heads and its underground storage against future national needs. This program was slated for termination by the fiscal year 1972 federal budget, but this termination has not been exercised because of a subsequent injunction against it, pending an environmental impact statement under the National Environmental Protection Policy Act. The Physics Survey Committee notes in passing the recommendation of the Committee on Resources and Man of the National Academy of Sciences-National Research Council (see *Resources and Man*, W. H. Freeman and Company, San Francisco, 1969) that deals with continuing such a conservation program.

RECOMMENDATION

FEDERAL GOVERNMENT

—The Congress

PHYSICS COMMUNITY

Chapter 4

44. The helium conservation program maintained during the period 1960–1970 should be continued pending new legislation to replace the Helium Act Amendments of 1960. The new legislation should provide, on a viable and stable financial basis, for the maximum technically feasible and economic extraction of wasting helium, with storage of the excess over consumption. It should also provide for discouragement of wasteful helium consumption and of the development of critical uses likely to depend on a helium requirement incompatible with long-term supply.

A NATIONAL SCIENCE STATISTICAL DATA BASE

Fundamental to any long-range planning at a national level is the availability of reliable statistical and other information concerning the various scientific disciplines. The only current coherent program for the collection of such data in the United States comprises the various NSF survey series, such as *Federal Funds for Research, Development and Other Scientific Activities* and the National Register of Scientific and Technical Personnel. These surveys do not give sufficient information broken down by disciplines to be very useful for long-range planning. The National Register, which is the most fruitful source of longitudinal data on scientific manpower and which has been maintained for over 20 years, is being terminated in fiscal year 1972.

In the present survey, as in all others previously, extensive effort has been devoted to the development of the pertinent statistical data for the field under study. Unfortunately, no mechanism exists for maintaining these individual field data bases on the completion of the survey activities, although maintenance would be relatively simple compared to the completely new start that has been necessary in the past whenever a detailed examination of any scientific discipline was undertaken.

A major problem, too, is the lack of agreement concerning the types of statistical data collected by, or available from, different agencies, the definitions of such central items as scientific man-years and of the boundaries of different scientific disciplines and areas of specialization, and the allocation of funds and manpower among activities ranging from basic research to product development.

RECOMMENDATIONS

FEDERAL GOVERNMENT

—Office of
Science and
Technology

SCIENTIFIC COMMUNITY

Chapter 12
Chapter 13
Chapter 14

45. A coordinating committee should be established by the Office of Science and Technology and the National Academy of sciences to develop, in collaboration with federal agencies, guidelines and definitions for use in the collection and reporting of manpower and funding data in major scientific, engineering, and other professional-technical disciplines. This committee should familiarize itself with previous and current efforts to clarify and coordinate federal reporting procedures and build on these efforts. It is essential that, to the greatest possible extent, intercomparability among the data from different disciplines be ensured.

SCIENTIFIC COMMUNITY

Chapter 12
Chapter 13
Chapter 14

46. The National Academy of Sciences, with funds provided by the National Science Foundation, should contract with the organizations representing major disciplines, for example, the American Chemical Society and the American Institute of Physics, to collect and continuously update manpower and funding data in these disciplines (drawing as necessary on existing compilations such as the National Science

RECOMMENDATIONS

Foundation's series on *Federal Funds for Research, Development and Other Scientific Activities*). Appropriate statistics on primary and secondary publications and other information-exchange media also should be compiled for each discipline. There should be a continuing program of operational research to assure that the implications of the data to be collected are developed and made available to all concerned audiences.

FEDERAL GOVERNMENT

—Support
Agencies

Chapter 12
Chapter 14

47. Recognizing that the National Science Foundation has the statutory responsibility to maintain a register of scientific and technical personnel and to make available such information, we strongly recommend that the National Register of Scientific and Technical Personnel, or an appropriate equivalent, be reinstated promptly. An important function of any such data compilation is to provide insight into systematic changes and trends. The Register data have only recently encompassed a time interval sufficient to be useful for this purpose. To permit an extended hiatus in statistical data collection would destroy the necessary continuity and detract from the utility of this resource.

DISSEMINATION AND CONSOLIDATION OF RESEARCH RESULTS

In many areas of science the problems involved in making the results of on-going research available to potential users have reached crisis proportions. The sheer volume of new research results, in the absence of effective consolidation and review, renders many of them inaccessible to most users. Several major activities are involved, including indexing, abstracting, current awareness services, and the preparation of critical reviews and data compilations in the different areas of specialization. Considerable progress has been made toward more-effective abstracting services, although much remains to be accomplished; the situation in regard to compilation and consolidation becomes increasingly critical. Chapter 13 of this Report considers these problems in detail.

RECOMMENDATIONS

SCIENTIFIC COMMUNITY

Chapter 13

48. All groups involved in the conduct or support of basic research should pay greater attention to the extent of dissemination of the journals in which they publish. The physics community should work even more strongly toward a system in which prerun costs of publication are borne by the research itself, and primary publications are distributed at runoff cost. The same consideration also applies to many kinds of secondary services, such as abstracts, and to critical reviews.

FEDERAL GOVERNMENT

—Support
Agencies

Chapter 13

49. All federal agencies supporting physics research should allocate a specific small fraction of their resources for grants and contracts that would help to fund the abstracting services that are necessary to make the results of their work known and accessible and the data compilation and consolidation activities that will make it more easily applied. With rare exceptions, such services are performed most effectively by continuing groups assembled specifically for the purpose, which, in the absence of such specific allocations, are frequently early casualties of budgetary limitations.

PHYSICS COMMUNITY

Chapter 13

50. The physics community should strongly support and encourage those of its members with the talent for, and interest in, preparation of critical reviews. In particular, preparation of such reviews should be treated on an equal basis with original research in terms of logistic and other ancillary support provided. Specifically, this should include support for postdoctoral and student assistants and for various types of computer and information retrieval assistance.

INTERNATIONAL COMMUNICATIONS

During the past 25 years, because of international pre-eminence in almost all fields of science, U.S. institutions experienced a steady influx of foreign students, postdoctoral fellows, and scientists. Those foreign scientists who remained in the United States contributed in very significant fashion to the strength of the U.S. scientific enterprise; those who returned to their homelands provided a strong nucleus for the development of stronger national programs in science. They also played an important role in interpreting U.S. aspirations to their countrymen and linking U.S. scientific activities with those in their countries.

As other national scientific programs increase in strength, dependence on the United States for leadership and training in science and the flow of foreign scientists to this country will decrease. As a result, the vital exchange of information between U.S. and foreign scientists will also decrease, unless measures are adopted to preserve and foster such communication. In addition, U.S. scientists increasingly will seek access to foreign facilities on a collaborative or user basis. Dollar for dollar at present levels, funds spent for these purposes probably yield a larger scientific return than additional funds for domestic research. Unfortunately, recent policy decisions concerning the use of federal agency funds for foreign travel or research at foreign centers and postdoctoral fellowship policies, particularly those of the NSF, have made such international activities increasingly difficult.

RECOMMENDATIONS

**FEDERAL
GOVERNMENT**
—Support Agencies
*Chapter 8
Chapter 11*

51. The National Science Foundation should reinstate and enlarge its program of postdoctoral and senior faculty fellowships. Other federal agencies should be encouraged to establish parallel programs.

**FEDERAL
GOVERNMENT**
—Support
Agencies
*Chapter 8
Chapter 14*

52. The present budgetary ceilings for foreign travel and for collaborative research at foreign facilities that exist in some agencies should be removed. They are detrimental to international communication and advancement in science. However, requirements for prior justification and for posttravel reporting adequate to ensure, and to document, proper use of the funds involved must be retained. Within these limitations, the allocation of available funds among travel, other foreign activities, and other aspects of a research program should be the acknowledged responsibility of the principal investigator in optimizing the overall research return for a given level of support.

**FEDERAL
GOVERNMENT**
—Support
Agencies
Chapter 14

53. In view of the particular importance to the nation of furthering scientific cooperation with its closest neighbors and the importance of travel in such cooperation, Canada and Mexico should not be considered as foreign countries within the context of federal foreign travel regulations.

PROGRAM PRIORITIES AND EMPHASES

Chapter 5 describes a series of criteria—intrinsic, extrinsic, and structural—for possible use in establishing program priorities and emphases. Intrinsic criteria are those relating to the potential of a field for fundamental new discoveries and insight into natural phenomena and are intimately related to the internal logic of the field. Extrinsic criteria are related to the potential benefits from interaction of a field with other sciences, with technology, and with society generally; they draw heavily on considerations external to the field. Structural criteria relate to both internal and external considerations, to questions of continuity, return on scientific and economic investments, interdependence of different scientific fields, and the like. The application of the first two of these classes of criteria is illustrated through detailed consideration of the program elements of each of the core subfields of physics in a jury rating sense. Because the structural criteria frequently require in each particular case a detailed knowledge of sociological, political, and other nonscientific factors for their evaluation, no equivalent detailed jury rating has been attempted. A recommendation wherein the structural criteria are of overriding importance will be found in the next section. In the selection of certain program elements for special consideration herein, however, structural criteria have been included implicitly, if not explicitly. In making this selection the Committee has considered the panel reports in Volume II in detail and, working with panel chairmen, has evolved the program elements for each subfield, as presented and discussed in Chapter 4. The selection has been based on the Committee consensus that in each case these were program elements wherein the gain in terms of new scientific knowledge, new applications, new technology, and new contributions to society would be especially large in proportion to the additional support required, provided that the specific projects and scientists were selected on the basis of excellence adjudged by their peers. Chapter 5 includes a detailed listing of the selected program elements.

It must be stressed that the selection of particular program elements for emphasis should in no way result in a compromise of the intellectual standards in the selection of individual projects. It is the Committee's expectation that the proposals and people associated with these selected program elements will probably be a little more interesting and of a little higher quality than those that might be associated with program elements to which a lower jury rating has been given. Furthermore, the Committee recommends that somewhat more benefit of doubt be accorded to projects in the selected program elements when they appear risky or controversial. At the same time, it should be clearly recognized that if only the selected program elements were supported, the overall physics research program would be totally unbalanced.

RECOMMENDATIONS

**PHYSICS
COMMUNITY**
**FEDERAL
GOVERNMENT**
–Support
Agencies
Chapter 5

54. The selected program elements discussed in Chapter 5 represent the core subfields of physics meriting incrementally increased support in terms of their potential return to physics, to science, or to society. It should be emphasized that this increased support should not be at the expense of eliminating support of other program elements, although clearly some readjustment is not only necessary but healthy as the different program elements attain different levels of scientific maturity. The physics community is urged to consider whether readjustment of its activities to place more relative emphasis on these selected program elements might be in order. The federal support agencies are urged to encourage such examination and to support increased activity where possible in these selected areas.

**FEDERAL
GOVERNMENT**
–Support
Agencies
Chapter 5

55. The criteria, the subfield program elements, and the procedures for applying the criteria to the program elements presented in Chapter 5 represent a first attempt at determining program emphases or priorities in a semiquantitative manner. Physicists, agency program officers, and review committees are urged, through study and application, to develop and refine this procedure further or to devise improved alternatives to the same end.

DEVELOPMENT OF FUSION POWER SOURCES

Occasionally, developments in a field of science or technology reach a stage at which the major impediment to substantial progress can be identified as the actual scale of activity in the field. In short, the fundamental scientific and technological questions have reached the point at which solutions and applications appear to depend in considerable measure on the level of effort, and a substantial increase in support might be expected to yield rapid and far-reaching returns. Before proceeding, the gamble must be balanced against the potential benefits.

The goal of fusion power, with its potential advantages in terms of cost and reduced environmental side effects, is of such significance to the nation and the world that the progress made toward its realization in recent years suggests that an enlarged national program directed toward achieving this goal is in order. Although we still cannot predict with confidence precisely when a self-sustaining fusion system will be demonstrated, there has been enough progress in the past several years to give distinct indication that this goal is attainable. Additional support seems to us an entirely worthwhile deployment of national resources.

In all these discussions the tendency to confuse fusion systems based on the deuterium-deuterium reactions with those based on deuterium-tritium should be avoided. There has been a tendency to combine the anticipated greater technical feasibility of the latter with the anticipated lower costs and lesser environmental problems of the former.

RECOMMENDATION

FEDERAL
GOVERNMENT
—Support Agencies
Chapter 4
Report of the
Panel on
Plasma Physics
and the Physics
of Fluids
(in Volume II)

56. The federal government should announce a commitment to a full-fledged pursuit of fusion power with the immediate aim of achieving a self-sustaining reaction, provided that no scientific obstacles are found that would thwart this aim. The program to achieve fusion should be an orderly but vigorous one, and additional appropriations to support this program should be made. Significant industrial participation in the proposed program would be essential for most rapid development and utilization of this new energy source.

AREAS OF STRUCTURAL URGENCY

At the present time there are several areas in which the structural criteria, which we define above and in Chapter 5, assume an overriding importance. These are found in the subfields of astrophysics, elementary-particle physics, and, to a certain extent, nuclear physics, where work at the scientific frontiers requires major facilities or instrumentation such as satellites, telescopes, or accelerators. Because of their large size and large unit construction and operating costs, such facilities tend to dominate the funding but not necessarily the manpower or level of activity in the respective subfields.

As discussed in some detail in Chapter 5, both the National Accelerator Laboratory (NAL) and the Los Alamos Meson Physics Facility (LAMPF) were approved and construction initiated during a period in the mid-1960's when support for physics was at an all-time high. In both cases there was a clear expectation that, while orderly termination or phasing down of some existing facilities was reasonable at the time of completion of the newer facilities, the support that could reasonably be diverted by the closing of these facilities would be much less than that required to operate and provide user funding for the newer ones, and that, while the new facilities would not be complete add-ons to the existing program, some incremental funding would be necessary and would be made available, if the overall program were to be scientifically viable.

These new facilities are now or will shortly be ready to begin operation. Yet, unless incremental operating funds are made available in fiscal year 1973, even fractional research utilization will be possible only at the expense of termination of significant segments of other research activities in their corresponding subfields. Despite the fact that a number of facilities have been closed since the mid-1960's, any flexibility that this might have introduced has been virtually eliminated by the leveling off of support in physics and the increasing costs of doing research.

The investment in these facilities, both financial and in terms of scientific man-years, their potential for research at the frontiers of understanding, and their importance to the future of their subfields are so great that the Committee believes failure to exploit their potential would be unacceptable. At the same time, operation of these new facilities at the cost of terminating support for one third of the personnel and three fourths of the existing installations in the corresponding subfields is regarded by the Committee as being equally unacceptable.

RECOMMENDATION

FEDERAL GOVERNMENT

—Support
Agencies

Chapter 5

57. The Atomic Energy Commission and the National Science Foundation should seek and the Congress should provide incremental appropriations in fiscal years 1973 and 1974 sufficient to permit orderly and effective initiation of research operations—both in-house and through user-group activities—at new research facilities as they are ready to become operational.

NATIONAL SUPPORT LEVELS FOR PHYSICS

From the start of its deliberations this Committee has realized that it is unrealistic to consider a single level of support that physics "must have" over, say, the next five years. Rather, the proper level of support will necessarily be a compromise in which the benefits of work in physics are matched against national resources and against needs in other areas. Consequently, the charge to each panel asked for an assessment of consequences to the subfield, and to the nation, that would result from each of several conceivable levels of support. Specifically, details of program, funding, and manpower were requested for several different program levels, which, as they finally evolved, can be described as:

1. *An Exploitation Program* designed to exploit all the currently foreseen opportunities, both scientific and technological, in a subfield and to maintain a healthy development program directed toward long-range future facilities and approaches.
2. *A Level Budget Program* designed to utilize a funding level held constant (after correction for inflation) in the most effective fashion.
3. *An Intermediate Program* designed to exploit a moderate growth rate intermediate between the above two programs.
4. *A Declining Budget Program* designed to explore the consequences of a funding level that, after correction for inflation, decreased at about 7.5 percent per year.

The panels responded to these challenges. Consequences to the programs at various funding levels were much easier to predict in subfields centering on large facilities than in others. What emerged from the panel considerations, with reasonable consistency, was that an annual growth rate of 11 percent in fiscal year 1970 dollars would permit full exploitation of the opportunities presented by each subfield. Chapter 5 shows, quite independently and following a rather detailed examination of manpower figures and projections, that this growth rate would also permit most of the 1500 new PhD physicists who could be produced in each of the next five years to be absorbed into the general U.S. physics endeavor (university, government, and industry), with an approximate annual 3 percent escalation in the real cost of doing research. Even at a full 11 percent growth rate through fiscal year 1977, again as illustrated in Chapter 5, U.S. physics support would not regain the level that it would have reached had it been possible to maintain a steady 5 percent growth rate since fiscal year 1967 when the field was in a state of robust health.

Consideration of the effects of level funding tends to show that a wide variety of interim measures, introduced throughout a subfield to maintain viability during a hopefully brief funding pause, will necessarily be institutionalized and made permanent. This situation can result in major and serious consequences.

The Declining Budget Programs, almost without exception, demonstrate that whole areas of the different subfields would be abandoned; U.S. physics would no longer be, as

it is at present, close to the forefront of progress in the great majority of areas. Contributions to the nation and to the national economy would be seriously eroded. In the face of burgeoning activity in other countries, the United States would find it necessary to accept a secondary role, attempting to retain a response capability such that important new discoveries, if not made in the United States, could nonetheless be exploited for U.S. society. The Committee believes that the U.S. public would not be willing to accept the consequences of such a situation. Development of declining budget programs, however, as is apparent in the panel reports, has forced a very salutary examination of the internal priorities in each subfield and has made more apparent the seriousness of the consequences of an extended period of deteriorating support, not only for science but for the nation.

Finally, the Intermediate Budget Program—typically involving a 6.5 percent annual growth rate—indicates the advances that can be made and the opportunities that can be followed up, as well as those that must be deferred or foregone. The individual panel reports of Volume II discuss all these programs in detail in terms of both support and manpower, in addition to their scientific consequences.

The fact that the Committee does not recommend a detailed national physics program appropriate to different possible levels of support in the growth range from 0 to 11 percent does not reflect an unwillingness to face the difficulties inherent in any such attempt. Rather it reflects the conclusion that it is impossible for such a group to develop either adequately complete information or insight to make such a detailed attempt meaningful. It is unrealistic to look upon the total support of U.S. physics as a reservoir from which funds for individual program elements may be distributed without cognizance of all the internal and external pressures and constraints within both the different funding agencies and the physics community. These, moreover, change rapidly with the magnitude of the overall funds available.

Furthermore, any detailed funding program for physics recommended by a single committee, no matter how wise, would tend to impart a rigidity to the effort that would soon become stultifying to further progress. Physics is a dynamic subject, which means that each major new discovery tangibly alters the priorities in the entire field. To recommend a funding plan that would inhibit responsiveness to such developments would be a serious disservice to the field. However, it is possible to provide a framework for evaluating the opportunities and needs of physics subfields according to various criteria. This the Committee has done and hopes that others will further refine and apply the procedure.

The pre-eminence of U.S. physics owes much to the complex process by which decisions determining the research to be supported by the nation are reached. It involves many working scientists, federal program administrators, economists, and legislators. In general, the science program is probably subjected to greater review than any other item in the federal budget. This Report represents only one small part of such a continuing review, but it has involved the efforts of several hundred physicists.

2. Priorities and Program Emphases in Physics

The determination of priorities in science is a dynamic, complex, and subtle matter requiring a balance among many different considerations ranging from the quality of the people in a field to the estimated value of potential applications. It is sometimes asserted that the scientific community has no system for determining priorities within science, and that the Federal Government has no policy for allocating scientific resources. Neither of these statements is true.

The Physical Sciences—1970
Report of the National Science Board

. . . Given adequate warning, academic science administrations are capable of judging priorities and shifting plans to meet overall limitations on Federal budgets.

Report of the Subcommittee on Science,
Research and Development of the
Committee on Science and Astronautics
U.S. House of Representatives
February 25, 1970.

This is an abridged version of Chapter 5 of *Physics in Perspective*, Volume I.

INTRODUCTION

During the 1950's and early 1960's, U.S. science, reflecting generous public support, enjoyed a period of unprecedented growth in both quality and scope. In this period almost every competent scientist and almost every good idea could find support without undue delay. Annual growth rates of between 15 and 25 percent were not uncommon. The results were new knowledge, new technologies, and a large body of trained manpower commensurate with this national investment.

Such a growth rate could not continue indefinitely, and indeed, in the period since 1967 the support of many areas of U.S. science has seen marked leveling or effective decline—this is particularly true of physics as illustrated later in Figure 2: When science funding is increasing, as in the past two decades, questions of priority receive little overt attention because worthy new projects and new investigators can be supported with little detriment to work already under way. With ample funding for new initiatives and the capacity to exploit new opportunities, it is relatively easy to maintain the vitality of the scientific enterprise; it is much more difficult to do so under conditions in which not all good ideas can find timely support and where many competent scientists cannot find professional opportunities that exploit even a part of their training. The nation is then in a position of being less able to gamble, and the cost of wrong choices becomes much higher. The question of priorities moves much more to the center of the stage and becomes much more critical to the successful performance of the scientific endeavor.

THE QUESTION OF PRIORITIES

Questions of priority, although often not made explicit, are an integral part of all human endeavor. Science is no exception. Scientists, science advisors, managers of science, and the scientific community must decide in one area or another what to do next and where to devote energies and resources. What areas of science are most worth pursuing? Which are most deserving of encouragement and support? These are difficult questions to which there are neither obvious answers nor, indeed, obvious methodologies for obtaining answers. Yet, they are the real questions now faced by all who are concerned with science and who are forced to decide what to do next. Decisions imply priorities, judgments that it is better to follow one course as against another—even if both alternatives have real merit. How then are priorities in science to be determined? What is the nature of such determinations?

It is necessary to be clear at the outset that determinations of scientific priorities are implied predictions. They are attempts to foresee the

scientific and practical consequences of specific courses of action under conditions of uncertainty. Decisions on priorities must take into account not only the most probable outcome but also the consequences of alternative possible outcomes. They must allow for keeping future options open in case matters do not turn out as foreseen. Because of this high degree of uncertainty, the best decisions are usually made by those who have to live with their consequences. Each scientist must decide, day by day, what he is to do in the future—what problems he will take up, what approaches he will use, how he will deploy the resources and talents at his disposal—for his rewards, tangible and intangible, and his life work are at stake. In doing this he must take into account the decisions and findings of many other scientists, so that in fact each individual decision becomes a part of a collective judgment of much larger scope, involving an implicit consensus of a large community.

It has been suggested that the scientific community should be able to devise a rational system for determining priorities within scientific fields and among scientific disciplines. After extensive discussion the Committee concluded that although the matter can be stated rationally in principle, the information that could provide a completely rational and explicit system of decision-making does not exist. In this respect the difference between science and many other activities is not so great as might be believed. Thus the nation does not have a rigorous basis on which to establish how much defense the country needs or how much education or how much health care or how much environmental protection. It is easy to state that one should continue to increase resources devoted to a given objective until the marginal return from such resources is less than that from alternative investments, but the calculation of such marginal returns in the future is guesswork, even when the uncertainties of prediction are much less than they are for scientific investigation into the unknown. In the absence of an analytical system, decisions are essentially reached by the complex of social processes within the scientific community and of social, political, and economic processes at the national level. The 1970 National Science Board report to the Congress reflects this:

The fact that much of science does not use a highly visible, centralized, priority-setting mechanism does not mean that other mechanisms do not exist. Actually, science uses a multiplicity of such mechanisms. One priority-setting mechanism operates when a scientist determines the problem on which he works and how he attacks it within the resources available. This determination is made taking into account other similar and related work throughout the world. Another mechanism operates as proposals of competing groups of scientists are evaluated and funded on the basis of systematic refereeing and advice of peer groups. Still another mechanism operates as aggregate budgets for various fields of science are influenced by the number and quality of research proposals received in that field. Like any market mechanism this system is not perfect and requires regulation and in-

puts from outside the system itself. Such inputs come from the mission-oriented agencies which balance their needs for new knowledge against their operating needs and from a whole host of outside judgments implicit in the budgetary and appropriation process. Trouble occurs either when these external judgments are completely substituted for the priority setting of the scientific community or when the priority setting of the scientific community becomes too autonomous.

In the affairs of science two forces are acting: those external to the science, which represent the aims of society, and those internal to it, which represent its natural development. Unless these forces are maintained in balance there is danger of collapse. If the external forces become too strong, the internal fabric—the unity of science, which is emphasized throughout this report—may be ruptured.

On the other hand, if the internal forces become too strong and science turns away from the society in which it is embedded, it runs the strong risk of becoming irrelevant.

Consideration of the external inputs from the mission-oriented agencies are essential, in the evolution of priorities. There is an important internal input that should also be emphasized. Academic scientists are especially sensitive to the interests and concerns of students who join the scientific enterprise with new ideas and values not completely determined by the perspectives acquired by the senior scientists in the course of their working lives. The continuing entry of able and energetic students into the scientific process tends to stimulate a continual re-evaluation of priorities among academic scientists and within the scientific community as a whole. The process of selection of faculty members for universities is itself another decentralized priority-setting mechanism.

Science is supported by the federal government and other institutions for a great many reasons. Physics directly and indirectly plays a role in such major national programs as defense, education, and industrial development. Decisions as to which fields of physics are to be supported have direct impact on the lives of many people and can have major impact on the future of major national research facilities and on national economic health. In any ultimate priority assessment these factors must also be taken into account.

Thus a discussion of priorities has a value insofar as it illuminates the nature of the political debate that must ultimately determine the allocation of resources. This Committee can assign no priority system that in any way can, or should, completely circumvent that political process. Our view is that of a group of physicists appraising the needs of physics admittedly from our viewpoint. We have tried, however, to look at issues and physicists from other points of view—e.g., the needs of the nation, the needs of mankind—how successfully we do not know. But information of this kind should be considered as one of the important elements that enters into the social, the political, and the market processes for deciding the allocation of resources.

APPROACHES TO THE ESTABLISHMENT OF PRIORITIES

As in so many other human affairs, a multiplicity of criteria must be brought to bear on scientific decisions. Thus, perhaps, the best way to approach the question of priorities in science is to try to identify and develop the criteria by which they are made. There is now an extensive literature in this area; as a Committee we have studied this earlier work and have devoted much effort to the evolution of a set of criteria that we have found particularly useful in appraising the needs and potentials of the different subfields of physics. A number of approaches that have been proposed for the establishment priorities are considered in the survey report together with what we as a Committee consider to be their positive and negative aspects.

THE DEVELOPMENT OF A "JURY RATING"

After much discussion of the various possibilities, the Committee decided upon an approach that combines many of their features: a "jury rating" of Committee members as to the appropriate emphasis that should be applied to a given activity within the next five years, taking account of both the internal, intellectual needs of physics and their assessment of the impact of these scientific developments on other sciences, on technology, and on societal problems generally. It must be emphasized that any such rating system has a value that is relatively short-lived, since science changes so rapidly. Moreover, any group of people as small as the Physics Survey Committee is bound to represent certain prejudices or special interests that would be different for a differently selected but equally competent group of comparable size. The numbers are too small for nonobjective biases to be mutually canceling.

The development of this "jury rating" involved two aspects. First, the Committee as a whole devoted extensive discussion to the evolution of a list of criteria. Second, working with the chairmen of the subfield panels each subfield was divided into a set of "program elements" that span the major areas of the subfield and could be evaluated in terms of the criteria. In our report, these elements are discussed at some length in an appendix to Chapter 4. This appendix is included in this condensed report.

The purpose of the ratings was to test the feasibility of arriving at a consensus regarding the desirable relative emphasis among subfields of physics and between program elements within each subfield. Such judgments might then guide decisions as to increased or decreased support for each program element and subfield within whatever total might become available for physics as a whole. It is the Committee's view that

the outcome of this exercise is properly described in terms of program emphases rather than priorities.

Thus the goal has been to identify those program elements in physics that, on the basis of our criteria, should experience large *relative* growth rates. The questions of *overall* growth rates and support levels for physics and development of contingency alternatives designed to respond most effectively to different levels of such total support are taken up later in this chapter.

THE DEVELOPMENT OF CRITERIA

In developing our criteria, three general categories appeared useful: *intrinsic merit*, *extrinsic merit*, and *structure*.

Intrinsic merit we define as criteria internal to science. *Extrinsic merit* is concerned with impact on technology and on the resolution of human problems. *Structure* is concerned with impact on the national capability to do physics. These three categories are not truly independent of each other. If science does not progress at a sufficient rate in terms of its own internal logic, it will contribute less to society, or its contribution will come either at much higher cost or with unexpected negative side effects, reflecting the undertaking of technological projects with inadequate understanding. If science fails to contribute to technology, it will lose an important source of intellectual stimulation and may fail to attract some dedicated and socially motivated people. The viability of the institutions of science depends on the intellectual thrust of their accomplishments, and *vice versa*.

Intrinsic Merit

Here the measure of merit is primarily scientific opportunity. What is the probability that work in a field will have a major impact on man's understanding of his world or of the universe? More precisely, which of several possible scientific strategies will most probably result in the greatest increment of insight or understanding for a given expenditure or resources (effort, money, and talent)?

Because of new concepts, new questions, new experimental or theoretical approaches, or new instrumentation and observational techniques, some fields promise more immediate rewards from exploitation than others, and this is clearly one of the most important elements of intrinsic merit. A related question, reflecting the unity of science, is the degree to which a particular program has the potential for illuminating the broader area of science of which it forms a part.

Will a new solution for the relativistic field equations provide the

basis for new understanding of the origin and nature of mysterious astronomical objects? Will a better theory of superconductivity in metals throw light on the theory of nuclear structure? Will an improved understanding of nuclear structure permit a better understanding of stellar evolution and the origin of the elements? More rare, but of vital importance, are those investigations that might open up whole new areas of investigation, as would be the case if experimental detection of gravitational radiation is confirmed or as happened following detection of isotropic background electromagnetic radiation in space. Thus under the rubric of intrinsic merit each scientific activity requires consideration not only in terms of its own frontiers but also in terms of the opportunities it offers for strengthening the whole fabric of scientific understanding.

The intrinsic merit of a field is also reflected in the quality of the scientists it attracts. In fact, the history of science shows that outstanding individuals make important contributions in any area that arouses their enthusiasm. Such individuals often make major contributions to several quite different areas during the course of their careers. The movement of a few outstanding individuals into a new area may be one of the surest indications that this field has become ripe for exploitation. This criterion recognizes that there are some individuals with such powerful scientific vision that their individual choices can be better trusted than those of any jury of experts. The mere fact that they are prepared to commit their own careers and reputations to a field is a compelling index to its intrinsic merit.

Extrinsic Merit

The contributions that one scientific field can make to others in terms of new fundamental insights have been noted.* There are extremely important, but more localized interactions, that are worth mentioning. The application of radioactive tracer and stable isotope techniques to the study of the circulation of atmospheric pollutants is one example. Another example is the transfer of concepts in the dynamics of nuclear reactions to the study of elementary reaction processes involving individual energy states of atoms and molecules in chemistry. A better theoretical model for turbulent fluid flow would illuminate large areas of the environmental sciences and of technology, which depend on the flow of fluids. These examples speak of scientific opportunity, but the potential benefits and new insights are primarily external to the particular area of science under discussion. In a real sense these are the benefi-

*Volume II provides many illustrations of the way in which increases in fundamental understanding of nature have influenced our capability for attacking practical questions of concern to society.

cial "externalities" of fundamental scientific investigation, which are more often than not unpredictable or can at best be anticipated through inspired hunch rather than logical extrapolation.

In addition to its impact on adjacent or even distant fields of science, an important criterion of extrinsic merit is its potential contribution toward opening up new technological opportunities. Is a proposed program likely to have an important influence on engineering development and design, on manufacturing processes, on protection or enhancement of the environment, on medicine, or on some other area relevant to human welfare?

The assessment of the technological opportunities arising from science has two aspects. First, a given scientific activity acts as a source of concepts and experimental techniques. For example, semiconductor technology, and ultimately the sophisticated techniques of integrated circuits and microelectronics, has emerged from deeper understanding of many different aspects of condensed-matter physics and of chemistry.

A second aspect, the more immediate symbiotic relationship between physics and technology, appears when a field of investigation draws heavily on adjacent areas of science and technology for concepts and techniques, often stretching the existing state of the art and often providing an incentive for technological development that would not initially be supported for its own sake because the potential applications are too distant, speculative, or actually unforeseen. For example, both nuclear and elementary-particle physics have drawn heavily on computer techniques, on high-power radiofrequency technology, on cryogenic engineering, on techniques for the production and measurement of high vacuums, and on the development of high-intensity ion sources and ion optics.

Another important criterion of extrinsic merit relates to the potential for rather immediate applications in other areas of science, engineering, or technology. The Doppler scattering of a laser beam from a high-energy electron beam to produce polarized gamma radiation is an illustration of application to several areas of science.

The potential contributions of physics to national security cannot be ignored. These occur not only directly in the area of defense capabilities but even more significantly in the area of disarmament and both unilateral and multilateral inspection techniques for the monitoring of arms control agreements.

Finally, there is the degree to which a given scientific activity may contribute toward public understanding of science and the extent to which it may lend itself to broad educational functions. For example, certain areas such as astronomy or space physics have a natural appeal to the public imagination that can serve as a means for communicating deeper understanding of physical principles generally. Similarly, areas

such as bioacoustics, which deal with phenomena familiar to everyone, contribute to formation of bridges of understanding between science and a naturally receptive public.

Structure

The criteria discussed so far implicitly assume that the proper percentage distribution of support across the subfields can be determined independently of the total amount available, or that the same relative distribution will optimize the research output for any total amount. This is obviously not true, at least in fields heavily dependent on large, costly facilities. Thus if intrinsic and extrinsic criteria alone are applied, the result is a distribution that assumes that the level of activity in the various research components comprising a subfield can be scaled up or down without affecting the viability of the subfield as a whole. Furthermore, there is here an implicit assumption that not only the subdivisions but the subfields themselves are, at most, weakly coupled to each other.

On the contrary, the pursuit of scientific goals has resulted in a complex and interdependent social system. Disturbances in one part of the system are often communicated throughout all scientific and technological activity, even in the absence of obviously direct connections. Thus support decisions must be viewed in terms of their impact on the institutional and communications system of science and on consequent changes in future national capability and capacity to respond quickly to new opportunities and needs. Here are some of the kinds of issues of concern:

(a) In the last few years several unique facilities requiring a large national investment of both talent and money, e.g., the Stanford Linear Accelerator (SLAC) and the MIT National Magnet Laboratory (NML), have been operated on greatly reduced schedules in order to save electrical power and other costs. Such decisions to reduce the rate of exploitation of past investments in a facility should be made deliberately for carefully evaluated reasons, not as an incidental by-product of an economy wave.

(b) The initial reduction in support of physics, beginning in 1967 was responded to by the physics community as though it were temporary. Short-term emergency measures were invoked to preserve capabilities in anticipation of renewed support in the future. Among these measures were deferral of exciting but highly speculative experiments, postponement of the upgrading of instrumentation, and reduction in the number of young scientists admitted to participation in frontier research activities. Rather than the widespread closing of laboratories and disbandment of research groups and graduate programs, which would have resulted in the concentration of support in a smaller number of remaining installa-

tions, the physics community responded by a more uniform belt tightening, a response that maximized future options. Over an extended period, however, the effort to keep future options open may result only in uniform decline toward mediocrity if the expected restoration of support fails to materialize, with no single group remaining competitive with its international counterparts. This would be the situation in which the total U.S. support of physics continued to appear large by international standards but no one group or activity received a sufficient fraction of the total to maintain itself in a leadership, or even competitive, posture.

(c) In certain fields, major national facilities—the Los Alamos Meson Physics Facility and the National Accelerator Laboratory, to give examples in nuclear and elementary-particle physics, respectively—were approved in the mid-1960's with the expectation that the operating funds required to exploit their research capabilities at the frontiers of these fields would be primarily incremental to the ongoing programs. During this coming year these facilities will begin large-scale research operation, and while the Atomic Energy Commission's funding projections reflect the need for incremental funding, such funding has not become available. Two possibilities confront the nation: either these newest facilities remain largely underutilized or the necessary funding is removed from other programs in the respective subfields. Inasmuch as costs per PhD research scientist at these new facilities are substantially higher than at older and smaller facilities, the latter course could cripple large segments of these fields. Although the availability of new frontier facilities will naturally result in the transfer of some scientific activities from older facilities, the cost savings do not compensate for the higher operating costs of new installations. Furthermore, the older facilities are often essential for obtaining data complementary to that obtainable with the new ones. Either of these possible solutions would be extremely wasteful of both talent and facilities. These again are structural considerations that must be dealt with in the evolution of any coherent national scientific program.

In view of these considerations an important structural criterion can be recognized: The extent to which incremental support, beyond the current level, is required in order to balance the need to capitalize on the national investments in large facilities and the equally important need to maintain the viability of the other components of the subfields in question. This is a critical time, in both respects, in the history of U.S. physics.

The needs of each subfield for major new facilities, both to maintain momentum of progress and to avoid loss of a world competitive position, merit consideration. In astrophysics, for example, there is a need for new receiving arrays and "dishes" for radio and millimeter-wave astronomy. Infrared astronomy is just beginning to develop. In nuclear

physics, heavy-ion accelerators offer access to an entirely new range of nuclear phenomena. This field was pioneered in the United States but is now being more actively pursued abroad.

Another structural criterion has to do with the effective utilization of existing facilities and instruments and the effective investment, per using scientist, in such facilities and instruments. It is much more costly to reach the frontiers of research in some fields than in others, and the costs per scientist may be correspondingly large. If various lines of scientific effort are judged to be equally valuable in terms of other criteria, those that require a smaller investment per scientist would, on a structural basis, tend to receive preference for funding. Such costs are difficult to quantify, however, and final judgment would probably remain qualitative. If cost per scientific paper is to be used as a measure, as sometimes proposed, are all papers to be treated as of equal value? How is the cost of instrumentation to be allocated among students, faculty, professional researchers? Is each use to be given the same weight? Somewhat arbitrarily, perhaps, the average cost per PhD scientist man-year in each subfield has been chosen here as reasonably indicative.

Table 1 presents estimates of these costs—operating and equipment—per experimental PhD physicist man-year in the different subfields of physics. Experimental research costs have been selected because the unit costs in theoretical work do not vary significantly among subfields; an average unit cost for a theoretical physicist at \$35,000 per year appears reasonable.

These costs must be viewed in the context of the importance of maintaining the essential unity of physics. As a parallel, within the Department of Defense the unit costs involved per air crew member of one of our more advanced aircraft vastly exceed those per member of an infantry corps; it would indeed be the height of folly to suggest that the former be eliminated in favor of more of the latter. Such questions, nonetheless, cannot be ignored entirely in overall consideration of priority establishment.

Two additional structural questions concern the manpower now available and now in training in each subfield. Any projected program must be predicated upon the availability of the necessary skilled manpower in that area. More important, however, is the question of balance between the rate of production of manpower in the field and the envisaged opportunities that are projected for them. This question is addressed in detail in Chapter 12 of Volume I and is one of vital importance to the future of the U.S. scientific community.

Perhaps less obvious, but also important, is the extent to which a given program element or subcomponent of a subfield is essential to the maintenance of the health of the scientific subfield of which it is a part. To cite a specific example, although atomic optical spectroscopy of it-

TABLE 1 Approximate Costs per PhD Man-Year in Experimental Physics

Physics Subfield	Operations and Equipment Costs ^a (\$ Thousands)
Acoustics	55
Atomic, molecular, and electron	50
Condensed matter	70
Elementary particles	175
Plasmas and fluids (excluding controlled fusion)	60
Controlled fusion	150
Nuclear physics	80
Astrophysics and relativity	55 ^b

^aCosts do not include amortization of major facilities.

^bWhen space-based research is included, the cost per year per PhD is approximately \$200,000. Thus research in this subfield, in common with astronomy generally and with high-energy physics, is relatively expensive.

self might be given a relatively low competitive rating at the present time, its vital importance to much of atomic physics, plasma physics, and astrophysics requires that it be maintained in a healthy state. Similarly, the development of lithium-drifted germanium crystals might receive a relatively low rating in condensed matter physics, but it is essential to large areas of contemporary nuclear physics as the basis for radiation detectors of unparalleled resolution.

CRITERIA FOR PROGRAM EMPHASES

Three sets of criteria have emerged from our discussions and were refined through application to program elements in the various subfields. Under each set questions were used to determine the criteria as follows:

Intrinsic Merit

1. To what extent is the field ripe for exploration?
2. To what extent does the field address itself to truly significant scientific questions that, if answered, offer substantial promise of opening up new areas of science and new scientific questions for investigation?
3. (a) To what extent does the field have the potential of discovering new fundamental laws of nature or of major extension of the range of validity of known laws?

(b) To what extent does the field have the potential of discovering or developing broad generalizations of a fundamental nature that can provide a solid foundation for attack on broad areas of science?

4. To what extent does the field attract the most able members of the physics community at both professional and student levels?

Extrinsic Merit

5. To what extent does the field contribute to progress in other scientific disciplines through transfer of its concepts or instrumentation?

6. To what extent does the field, by drawing upon adjacent areas of science for concepts, technologies, and approaches, provide a stimulus for their enrichment?

7. To what extent does the field contribute to the development of technology?

8. To what extent does the field contribute to engineering, medicine, or applied science and to the training of professionals in these fields?

9. To what extent does the field contribute directly to the solution of major societal problems and to the realization of societal goals?

10. To what extent does the field have immediate applications?

11. To what extent does the field contribute to national defense?

12. To what extent does activity in the field contribute to national prestige and to international cooperation?

13. To what extent does activity in the field have a direct impact upon broad public education objectives?

Structure

14. (a) To what extent is major new instrumentation required for progress in the field?

(b) To what extent is support of the field, beyond the current level, urgently required to maintain viability or to obtain a proper scientific return on major capital investments?

15. To what extent have the resources in the field been utilized effectively?

16. To what extent is the skilled and dedicated manpower necessary for the proposed programs available in the field?

17. To what extent is there a balance between the present and envisaged demand for persons trained in the field and the current rate of production of such manpower?

18. To what extent is maintenance of the field essential to the continued health of the scientific discipline in which it is embedded?

APPLICATION OF THE CRITERIA

One of the difficulties in applying the criteria is that of establishing the relative weighting of the intrinsic and the extrinsic criteria. This was again subjected to a "jury procedure" in the Committee in a variety of ways involving both weighting of the individual criteria and of the three areas—intrinsic, extrinsic, and structure—more generally. A consensus that was surprising to the participants was found. In this, the intrinsic and extrinsic criteria were assigned roughly equal weight, and the structure area about one third of the other two, although considerable spread in the weighting of each individual criterion was found. Recognizing the inherent lack of precision in any such process, the Committee gave unit weight to each question within each of the three categories. When a question has two parts, as in 3 and 14, each part was assigned this same unit weight. Indeed, the reason for listing these questions together rather than as separately numbered entries was to emphasize the close connection between them rather than to reduce the weighting of each individually. Inasmuch as the number of extrinsic criteria is roughly double the number of intrinsic ones, a relative weight of one half was assigned to each extrinsic criterion in our jury rating exercise; likewise, each structural criterion was assigned a relative weight of one third.

To illuminate the criteria through trial application to actual cases (and it should be noted that this process resulted in extensive modification of the Committee's initial criteria), and to discover the degree of consensus that existed within the Committee, matrices were prepared bearing the program elements of each subfield (see Chapter 4) as rows and the above criteria as columns.* The structural criteria were not included in this exercise because, to a much greater extent than those of an intrinsic and extrinsic character, the structural questions are of a detailed nature, applicable to each specific project, and they change rapidly with time. In arriving at ultimate program emphasis decisions, these structural criteria must be given due weight, but in order to apply them effectively a detailed study of the individual program elements, and of the individual research projects in them, is required. Certain exceptional

*This procedure was applied only to acoustics; astrophysics and relativity; atomic, molecular, and electron physics; condensed-matter physics; elementary-particle physics; nuclear physics; optics; and plasmas and fluid physics. The interface fields such as chemical physics, biophysics, and earth and space physics present special problems and were not considered amenable to this approach. In large measure this reflects the fact that the physics components of these interface areas, although very important, are not dominant. Lacking a more comprehensive survey of these fields to place the physics elements of these fields in better perspective, we have not considered ourselves competent to carry out a similar jury rating.

cases for which the structure criteria have a direct bearing on our recommendations are discussed below.

With the reports of subfield panels in hand, and following a brief presentation of the program elements by an advocate drawn from the Committee membership, the matrix elements were rated on a 0-10 scale by each Committee member. These ratings were subsequently combined to obtain the averaged matrices for each subfield.

Figure 1 is the averaged rating histogram plotted in this fashion for the above-mentioned eight internal subfields of physics. Inasmuch as questions 4, 11, and 13 are of a somewhat different character than the remaining ones, they are presented in a separate histogram to the right of each figure. (Histograms of the Survey Committee average jury ratings of the individual program elements in each subfield appear in Chapter 5.) Several interesting checks that give a characteristic signature for each subfield emerge immediately from inspection of this figure. Not unexpectedly, acoustics and optics have a signature that strongly emphasizes the extrinsic criteria, whereas astrophysics and relativity and elementary-particle physics emphasize the intrinsic criteria. The remaining subfields fall between these extremes in ordering, a result entirely consistent with the intuition of the Committee members. Again, in terms of the ancillary histogram representing criteria 4, 11, and 13, astrophysics and relativity and elementary-particle physics were given the highest ratings consistent with the corresponding subfield signatures.

Most important was the fact that, despite widely different backgrounds and interests, the spread in the ratings of the Committee members on individual matrix elements was small. In part this is a reflection of the fact that the relatively large number of criteria that the Committee chose to use makes for a more objective evaluation of each individual criterion.

To obtain a characteristic score for each of the program elements within an intrinsic-extrinsic framework (but without inclusion of structural criteria for reasons given above), the averaged Committee ratings (with the relative weights of 1.0 and 0.5 applied to the intrinsic and extrinsic criteria, respectively) were summed. The last section of this chapter is an ordered listing so obtained. We would emphasize that the overall scoring was spread rather uniformly over the entire range covered by this listing; therefore, *within any restricted area of the listing the relative ordering should not be considered significant.*

We were again encouraged to believe that application of our criteria gave due weight to both extrinsic and intrinsic criteria inasmuch as the first four items on this overall score listing alternate between those having marked extrinsic and intrinsic ratings, respectively.

Recognizing that different support agencies and different readers of

C. 2

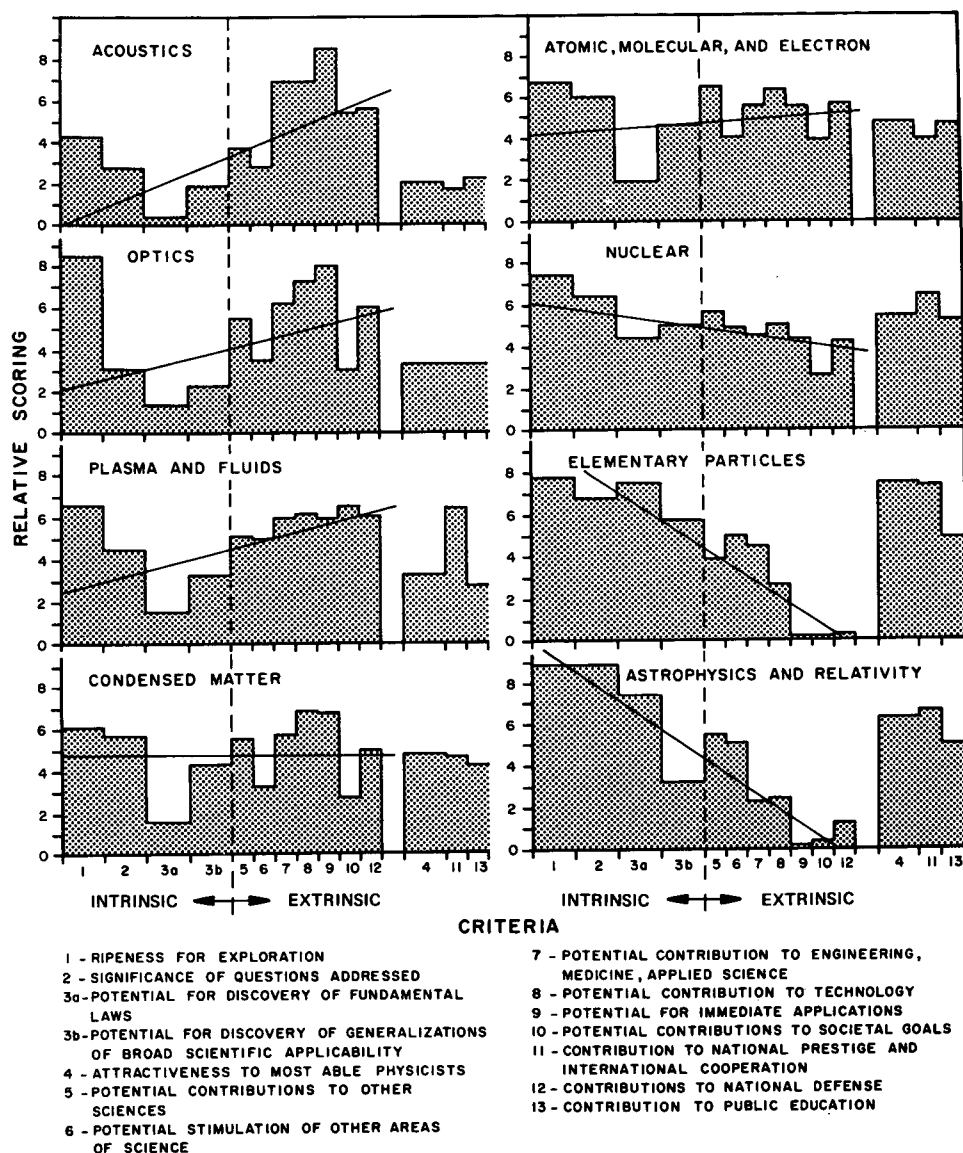


FIGURE 1 Histograms of the Survey Committee average jury rating of the internal physics subfields in terms of the intrinsic and extrinsic criteria developed in this report. The straight lines superposed on the histograms are simply drawn to provide a characteristic signature for each subfield. It is interesting to note that these signatures divide naturally into three classes with emphasis shifting from intrinsic to extrinsic areas as the subfield matures.

this report will wish to apply their own relative weightings to the intrinsic and extrinsic criteria, ordered listings in terms of the scoring for each program element in terms of these criteria considered individually are included in the last section of this chapter. Again *the same qualification concerning the significance of relative ordering in any restricted section of the listing applies.*

Emphasis again is necessary on the fact that these ratings represent the result of a single exercise by the members of one committee and unquestionably reflect their individual biases and special interest to some extent. Nonetheless, the degree of unanimity that was achieved was surprising. It cannot be emphasized too strongly that priorities change with time—often very quickly—as suggested in the 1970 National Science Board report to the Congress:

Dynamic, complex, and subtle systems for setting priorities are common in everyday life. A fire in the home or a sick child may instantly change a man's priorities. Such effects also exist in our political sector.

The approach adopted herein and the criteria evolved may have rather general utility in providing a somewhat more coherent and objective evaluation of program emphases than the more subjective intuition and folklore that has tended to characterize previous attempts of the scientific community. The specific listings, and indeed the selection of the program elements themselves within the different subfields, are all clearly open to discussion and argument; they should be taken as representing only an illustration of this approach to program element evaluation. To the extent that they are based on informed judgment by a group of relatively experienced physicists—drawing heavily on the detailed technical subfield reports—they may be of use in any establishment of program emphases within the national scientific enterprise.

The Committee's inability to formulate priority allocations based on some fundamental policy or underlying rational scheme does not result from a desire to evade this most critical question. However, after discussing the matter at length and reading the relevant literature, it concluded that an objective, rational, and systematic basis for the allocation of resources to science or within science does not exist at the present time, just as one does not exist in most areas of resource allocation for the public sector. The best that can be produced is an informed judgment based on experience and the knowledge of possible developments in the various fields. The conclusions presented are to be considered as those of a jury, informed but not necessarily impartial.

Utilization of these criteria will be discussed further following the next section of this chapter.

NATIONAL SUPPORT LEVELS FOR PHYSICS

Thus far, consideration has been given to the distribution of a total level of funding, allocated to the national physics enterprise, among the sub-fields of physics without explicit consideration of what that total level might be. It is abundantly clear, however, that the distribution is inevitably a strong function of this total level.

Support Levels for Science and the State of the Economy

There has been much discussion in recent years of possible mechanisms for establishing levels for long-term federal support of science; a number of them have been summarized by York.* More detailed discussions of the many problems involved may be found in the series of essays in *Basic Research and National Goals*.† Although now some seven years old and written near the end of a period of unprecedented growth, these essays retain a remarkable validity under present conditions.

What is clear, and what is the prime topic of Chapter 8 is that the preparation of a longer-range plan for the support of science than has been available until now should be considered of great importance at the highest governmental levels if the nation is to damp the destructive fluctuations in both manpower and funding induced by discontinuous changes in federal support such as those dating back to 1967.

Among the most discussed mechanisms for the establishment of long-term support levels for science have been these:

1. Tie the support of science to the Gross National Product (GNP). (See discussion of the GNP in Chapter 4.)
2. On the basis that the scientific community was in a state of robust health in 1967, tie projected support levels from that point to the GNP; this leaves an obvious present deficit which would require rectification by step funding increments in the short-range future.
3. On the basis that a healthy U.S. scientific enterprise is of particular importance to the well-being of our high technology industries and of these in turn to the national economic health, tie projected supported levels to the productivity of the high technology sector of the national economy.‡

*C. York, *Science* 172, 643 (1971).

†Committee on Science and Public Policy, National Academy of Sciences, *Basic Research and National Goals*. A Report to the Committee on Science and Astronautics, U.S. House of Representatives (U.S. Govt. Printing Office, Washington, D.C., 1965).

‡*Technology and International Trade: Proceedings of the Symposium sponsored by the National Academy of Engineering at the Sixth Autumn Meeting,*

The first two of these mechanisms assume that the support level of an activity such as basic research, which directly or indirectly derives a major fraction of its support from public taxation, should be coupled to the GNP or some such indicator of the state of the national economy. For an activity such as physics, which has a strong role in the national scene and which is tied back to the GNP through its linkages with technology, for example, such a simple coupling may be wrong not only in magnitude but even in phase. Two simple examples are pertinent. If the GNP were to drop steadily over a few years, the diagnosis could well be that this reflected the failure, on the part of the nation, to maintain a suitable level of development of new technology—a level that is increasingly linked to the health of the research enterprise. Such a diagnosis would suggest that a *decreasing* GNP should be reflected in an *increasing* support of basic research. On the other hand, if the GNP were to rise rapidly for a few years, a tight, in-phase coupling of physics support to it could well result in the unstable dynamic situation in which U.S. physics now finds itself following the rapid growth in the early 1960's. Thus any such direct coupling of physics support—or indeed that of any science—to the GNP is overly simple; indeed when the GNP is not increasing at a reasonably steady rate, such coupling could have strong negative consequences.

Similar arguments apply to the possible coupling of support levels to the high technology component of the economy. In this case, an additional problem involves the question of definition of what constitutes high technology; in some discussions the argument has come full circle, and high technology areas are implicitly defined as those that enjoy a positive balance of trade posture!

Although a number of areas in physics can be correlated with industrial activity, and such concepts as return on investment can be used, examination of the above suggestions in turn reveals no objective mechanisms for determining an appropriate level of resource allocation even in these cases. Even more serious difficulties are encountered in assessing the proper level of research to be undertaken in areas at the forefront of scientific exploration (e.g., elementary-particle physics, astrophysics, and cosmology, which have no present or even foreseeable direct impact on technology and industry). There it becomes necessary to fall back on the difficult process of estimating what will be required in resources to maintain these fields at an appropriate level of vigor. These fields interact in a complex manner with other fields of physics much closer to the technological and industrial enterprise, but it is impossible to do more

than make informed estimates as to what a field requires to maintain it in a healthy and vigorous state.

Other Considerations

The problems are compounded by the fact that, in practice, funding finally made available to the subfields of physics is not interchangeable. Lack of recognition of this fact has already led to tensions within the physics community and even within subfields of physics. There have been recent publications that both implicitly and explicitly questioned whether a substantial component of the present funding for space and elementary-particle physics should not much better be redirected toward subfields such as condensed matter or atomic physics in which the connection to societal needs is much more obvious. In the case of elementary-particle physics, for example, it has been argued by some that by deferring the start-up of the National Accelerator for some months it might have been possible to avoid the closing down of the Princeton-Pennsylvania Accelerator and the operating restrictions that have been necessary at the Stanford Linear Accelerator. Similarly, in nuclear physics, some have argued that by deferring start-up of the Los Alamos Meson Physics Facility it would have been possible to avoid the recent termination of a number of federal grants and contracts supporting large existing facilities in the field. We believe that such arguments are unrealistic, and that they do not properly include the extent to which the Congress responds to individual opportunities in science rather than to science as such. In the two specific subfields in the latter examples, moreover, the Panels have reaffirmed the importance, from the viewpoint of the internal logic of their disciplines, of moving forward vigorously on the new frontiers that these major new facilities make accessible.

A further important point is illustrated in nuclear physics where a significant fraction of the basic research is supported by the Reactor Division and the Division of Military Applications of the Atomic Energy Commission in fulfillment of their long- and short-range mission objectives. In any recommendation concerning the redistribution of funding aimed at optimizing the overall health and balance of nuclear physics, redistribution of this rather specific mission support might also appear desirable. This approach, however, may frequently be unrealistic because of the limitations on overall program flexibility, resulting from the facts that a significant portion of the work stems from mission requirements and some of it must be done in-house. The problem of competing objectives is in no sense unique to nuclear physics.

This does, however, raise a central issue: it is extremely important for science, for physics, and for the nation that a multiplicity of support

channels be maintained. Thus while much research, particularly that which is more extrinsic in nature, will find support from one mission agency or another, the National Science Foundation (NSF) with its primary scientific mission is able to support the more highly intrinsic research so necessary for a balanced program and the health of science.

There are other problems inherent in any attempts to make recommendations for the long-term support level for physics—or indeed for any science. To what aggregate of activity does the recommended total refer? If it is all academic science, how is the funding of national centers to be included? Is funding for user groups at these national centers included in the total or is only that fraction of the funding utilized by academic groups included? How is industrial support to be taken into account—as in condensed-matter physics, for example, in which industrial and federal support are roughly equal in the United States, or in optics and acoustics, in which the major support is from industrial sources? If part of the funding of the National Cancer Institute were to be used to support a pion irradiation facility for a university affiliated hospital, would this count as academic physics funding? How is funding to universities under the NSF-RANN (Research Applied to National Needs) program to be counted when some of this funding supports basic as well as applied goals?

Because information on the level of industrial funding of the different subfields is frequently unavailable, reflecting internal policy decisions that are generally based on proprietary considerations, the Survey Committee has directed its attention to federal support of basic physics research, which is the major source of funds.

History of Physics Funding

Figure 2 presents the level of federal funding during the fiscal years 1958 through 1972 with a partial decomposition into the major subfields. Also shown for comparative purposes are the recommendations of the physics survey completed in 1965* and the level that would have been reached following fiscal year 1967, had an annual growth rate of 5 percent been possible.

Table 2 is a more detailed listing of the *federal* funding in fiscal year 1970 and its distribution over the physics subfields both internal and external. In these latter three external or interface areas—earth and planetary physics, physics in chemistry, and physics in biology—the best available data pertinent to the specifically *physics* component of the

*Physics Survey Committee (G. E. Pake, chairman), *Physics: Survey and Outlook* (National Academy of Sciences–National Research Council, Washington, D.C., 1966).

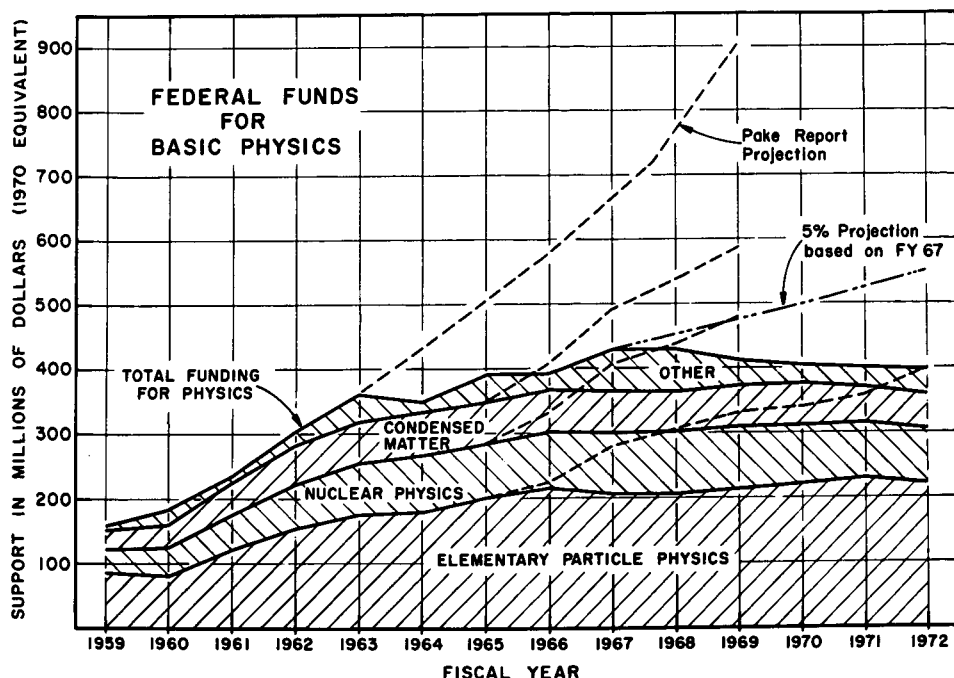


FIGURE 2 Federal funds for basic physics during the period FY 1959 through FY 1972. Also shown for comparison are the Pake report projections for three major subfields and for the total support of basic physics and a 5 percent projection based on FY 1967. Space physics and all of astrophysics and relativity have been excluded from these figures because of the definition problem involved in correctly allocating NASA funding to basic research. These detailed values for subfield funding do not agree with those given in Table 2 or in the Panel reports in Volume II, again because of questions of definition. In this figure we have included construction funding for elementary-particle and nuclear physics, together with operating and equipment funding.

subfield are included in the table footnotes. At best these data are only approximate. In earth and planetary physics, small changes of definition within the NASA program, as, for example, whether the cost of space vehicles is or is not included in the direct research funding, can give the appearance of very large relative changes.

Development of Contingency Alternatives

It was recognized from the outset of the Survey that in view of competing claims on the discretionary component of federal resources in any given year, it may not be possible to allocate to any given subfield that support that would permit it to make optimum progress. Therefore a range of contingency alternatives in each subfield was developed, repre-

TABLE 2 Operating Costs for U.S. Basic Physics Subfields^a (FY 1970, \$ Millions)

Physics Subfield	Federal Funding	Percentage of Total Federal Funding	Estimated Industrial Funding	Total Federal and Industrial Funding	Percentage of Total Federal and Industrial Funding
Acoustics	14	3	1	15	3
Astrophysics and relativity ^b	60	13	0	60	11
Atomic, molecular, and electron ^c	13	3	7	20	4
Condensed matter	56	12	80	136	24
Nuclear ^d	73	16	2	75	13
Elementary particles	150	33	0	150	27
Plasma and fluids	77	17	10	87	16
Optics	12	3	7	19	3

^aThe interface subfields, physics in chemistry, earth and planetary physics, and physics in biology, are not included in this table because the Panels have been unable to develop equivalently well documented funding estimates for these fields. In the case of physics in biology, only rough limits can be established. The membership of the Biophysical Society now stands at 2500, and at \$50,000 each this would correspond to an annual total (federal and industrial) funding of \$125 million. Most of this work is applied, however. In the Physics Section of the National Register some 200 persons are identified as biophysicists; on the same basis this would put a lower limit of \$10 million on the funding in this area. The Panel on Physics and Chemistry places the total support of chemical physics between \$150 million and \$200 million. Federal funding of the physics component of earth and planetary physics may be of the order of \$200 million.

^bOnly that part of the subfield that is heavily physics related is included.

^cA substantial amount of activity is supported from sources outside the AME subfield, e.g., plasma physics and chemistry. If included, this may double the above numbers.

^dThe federal entry includes \$12 million in funding for nuclear physics supported under chemistry.

senting an assessment from the physics community of means of obtaining the most effective utilization of whatever funding support becomes available—most effective from the viewpoint of the overall health of physics and of the contribution that physics can make to U.S. society.

Accordingly, the initial charge (Appendix C to this summary report) to subfield panels requested that they develop as detailed as possible programs for their subfields under various assumed funding projections: (a) a so-called exploitation budget that attempts to exploit all the opportunities, both intrinsic and extrinsic, now perceived; (b) a level budget—level in dollars of constant buying power; and (c) a declining budget—declining at an arbitrarily established rate of between 6 and 7.5 percent per year. To obtain the hoped for interpolation possibilities, it was necessary to evolve an intermediate-growth-rate budget between the exploitation and the level budgets. In each case, the Panels were asked to emphasize the costs to science and the nation of cutting back from the exploitation budget. This required very detailed examination of the internal structure of each subfield and of its opportunities and needs. It also required sharp scrutiny of the internal priorities of the subfield.

Development of such budgetary projections was more easily accom-

plished in some subfields than in others. In areas such as elementary-particle physics and astrophysics—and to an increasing extent in nuclear physics—the activity is largely quantized around major facilities. It is characteristic of such facilities that a large fraction of their total operational costs are invariant to the extent that the facility is maintained in operational status; support and developmental staffs, power for magnets, radiofrequency sources, and other systems must all be provided unless the facility is closed down. This is reflected in a very large leverage factor; that is, what appear to be very small percentage changes in the overall operational budgets of such facilities can be reflected as major fractions of the discretionary component of these budgets—that fraction that goes directly to the pursuit of research and not simply to keeping the doors open.*

In such heavily quantized subfields, reductions below the exploitation budget typically have involved the closing down of entire facilities or at least major change in the style and scope of operation permitted. This results in a corresponding reduction of the manpower that the subfield can accommodate, quite apart from possible opportunities for new personnel now being trained. The dislocation and career disruptions involved here for excellent scientists and support personnel (detailed in Chapters 6 and 12) is a wastage of resources, which in our opinion the nation can ill afford.

In less-quantized subfields such as condensed matter and atomic, molecular, and electron physics the effects of budgetary reductions are less obvious and the manpower problems less extreme. Because the research is much less facility-intensive, reduced funding means that the objectives of each scientist or scientific group are lowered—less work is done, fewer challenges are met, and the field slows down. While this can proceed for a time without overt symptoms of serious trouble, trouble is there; the morale drops, enthusiasm dwindles, and the subfield is less able to respond to challenges or opportunities. Quite apart from these differences, however, all subfields (see Volume II) have concluded that a budgetary level declining at 7.5 percent per annum would, within five years, bring the subfield below that critical point where productivity, however measured, falls dramatically.

We return then to the specific question of the appropriate support level for a scientific field such as physics. In summary, as there does not appear to exist any objective mechanism that can properly define this

*An excellent discussion of some of the problems involved here is given in the essay by H. Brooks in the above-mentioned *Basic Research and National Goals*; the problems that he addressed in 1964 are simply much more acute in 1971. Additional discussion of this same topic—but from a quite different viewpoint—appears in the essay by C. Kaysen in the same publication.

level in terms of considerations wholly external to the field itself, the Committee thus addressed themselves to an examination of what levels are indicated by internal considerations—in which, however, all the criteria, intrinsic, extrinsic, and structural, discussed earlier in this chapter are included.

An Exploitation Funding Level

Analysis leading to this funding level has been carried out in detail by the Panels on Elementary Particle Physics and Nuclear Physics. These subfields, in which activity centers on relatively large accelerators, are thus ones in which the consequences of a given level of funding are easier to specify than is the case for such subfields as condensed matter, where research requires less dependence on major, shared facilities. Many aspects of astrophysics and relativity have the same facility-oriented character as do elementary-particle and nuclear physics, but in the former it is difficult to separate the physics and astronomy parts of the funding, to say nothing of the difficulties in properly allocating NASA support in this area. Accordingly, the initial discussion hereafter focuses on elementary-particle and nuclear physics for which statistical data are complete and budget projections most detailed.

Both the Panels on Elementary Particle and Nuclear Physics have arrived at exploitation budgets growing at the rate of about 11 percent per year for the period through fiscal year 1977; the detailed processing leading to this common level has been distinctly different in the two areas (see panel reports in Volume II). In both cases, however, a significant shift of activity is envisaged to major national facilities—to the National Accelerator Laboratory in elementary-particle physics and to the Los Alamos Meson Physics Facility and a hoped-for national heavy-ion science facility in nuclear physics. In both cases this shift would involve effective or actual termination of a number of smaller facilities on university campuses and a corresponding change in the style of the typical research program.

During the five-year period for which these panels prepared detailed forecasts and descriptions, the exploitation funding budget would bring the level of activity in these fields near that which could have been sustained if funding support had increased at a rate of five percent per year since 1967. The annual increase of 11 percent should be looked at as a rebound or catch-up phenomena to allow these fields to regain a state of health and vitality sufficient to optimize their contributions to society and provide a solid base for future activity and productivity. As discussed below, and is immediately obvious, such a rate of growth could not continue indefinitely.

To take advantage of the opportunities now available in both cases requires vigorous exploitation of the new frontiers and aggressive capitalization on the possibilities now in the early stages of development. While the programs underlying the exploitation budgets in these fields were evolved without direct reference to the availability of trained manpower, it is clearly essential that this aspect of the fields receive full consideration in determining the extent to which the proposed exploitation budgets are realistic. A detailed manpower study, based on actual counts of students now in the educational pipeline and to be graduated during the period through 1977 and the assumption that the fraction of those physicists trained in these fields who remain in them would remain the same as was the case in 1967 (see Chapter 12) if adequate funding levels were to be restored, leads to an annual increase of 8 percent in the number of scientific man-years in each field.

The residual 3 percent difference between the 8 percent manpower growth rate and the projected 11 percent funding growth rate may thus be viewed as reflecting the effective escalation factor of the real cost of doing research. The available statistical evidence bearing on this question is not complete; however, in a recent NSF study, price inflation is estimated to have accounted for approximately a 50 percent increase in the *direct* costs of academic research and development over the period 1961-1971.* Most of this took place in the last five years when the average inflation rate was about 5-6 percent a year—a greater rate than the GNP deflator until 1969; about the same or slower since. The main factor in the change has been the slowdown in PhD salary increases since the appearance of a much more competitive employment market. Since PhD's may well remain in relative surplus, or at least not in tight supply, for the next several years, a research cost inflation is likely to be less than that in the cost of living since a major fraction of the total cost appears in the form of salaries, and these will almost certainly decline relative to the general wage level. In some instances, particularly in big science, this factor may be offset by rapid escalation of power costs due to environmental considerations. This will apply to accelerators and other installations for which a high proportion of the operating costs are expenditures for power.

Reflecting the greater flexibility that characterizes the remaining internal subfields of physics, where, in the absence of major facilities, relatively large fluctuations in support are reflected in an equivalent expansion or contraction of the scope of the activities of the individual researcher, or research group, the remaining panels have not found it possible to evolve correspondingly detailed budgetary projections. How-

*Science Resources Studies *Highlights*, NSF 71-32 (National Science Foundation, Washington, D.C., November 1, 1971).

ever, inasmuch as elementary-particle and nuclear physics together represent some 49 percent of the total federal funding of physics of the subfields shown in Table 2, it appears reasonable to adopt the 11 percent per annum exploitation budget level recommended by these panels as appropriate to *all* of physics.

As a first check on the more general appropriateness of this growth rate, the projected overall physics manpower situation was examined, drawing on the discussions in Chapter 12 of this report and on the study of the Grodzins Committee.*

In considering an exploitation funding level within the definition used throughout the survey, the situation characteristic of 1967, when some 90 percent of the new PhD physicists could be considered as a new increase of those active in the field, serves as an appropriate base. That the production of new PhD's in physics in the United States will stabilize at roughly 1500 per year during the period through 1977 is also a reasonable assumption, in view of the number of students already in training.

Grodzins found that of the 20,000 PhD physicists in the United States, 10,000 are in universities, 5000 in industry, and 5000 in government federally funded research and development centers (FFRDC) and other laboratories. For estimating purposes we consider those in universities and in government laboratories to be engaged in basic research, while those in industry are not, recognizing that clearly this is not completely true but assuming that the basic researchers in industry are effectively balanced by those doing applied research in government laboratories. In converting to effective scientific man-years (SMY), a factor of 0.5 has been used for university workers and 1.0 for those in government laboratories, resulting in a total effective 10,000 SMY (PhD level) now engaged in basic physics.

Taking 90 percent of the 1500 new PhD graduates per year as representing those retained in physics gives 1350 physicists. Converting to scientific man-years by the same factor (10/15) as used above results in a 900-SMY effective increase per year—a 9 percent manpower increase overall as compared with the 8 percent quoted above for elementary-particle and for nuclear physics. With such a 9 percent manpower increase, the projected exploitation budget growth rate of 11 percent per annum then corresponds to a minimal 2 percent allowance for escalation in the actual costs of doing research.

The net outcome of this exercise, however, is that the 11 percent annual growth rate projected for *all* physics, on the basis of the detailed

**The Manpower Crisis in Physics*, Special Report of the Economic Concerns Committee (The American Physical Society, New York, April 1971).

Elementary Particle and Nuclear Physics Panels studies, is consistent with the trained manpower now identifiable for the period through fiscal year 1977.

It is pertinent to ask whether such a growth rate would not again induce the type of oscillation in support and manpower that characterized the mid-1960's and that underlies some of the current problems now facing physics in the United States. Clearly, too, it is unrealistic to anticipate that such an annual growth rate could, or indeed should, be maintained over any extended period unless major steady growth of the national economy were to occur over an equivalent period.

At the same time it is extremely important to emphasize that, as shown in Figure 3 there has been a dramatic turnover in the operational support of U.S. physics since 1967, with a myriad of consequences, which are considered in Chapter 6 (and elsewhere) in the Report. Also shown in Figure 3 is the fact that even by 1977 a growth rate of 11 per-

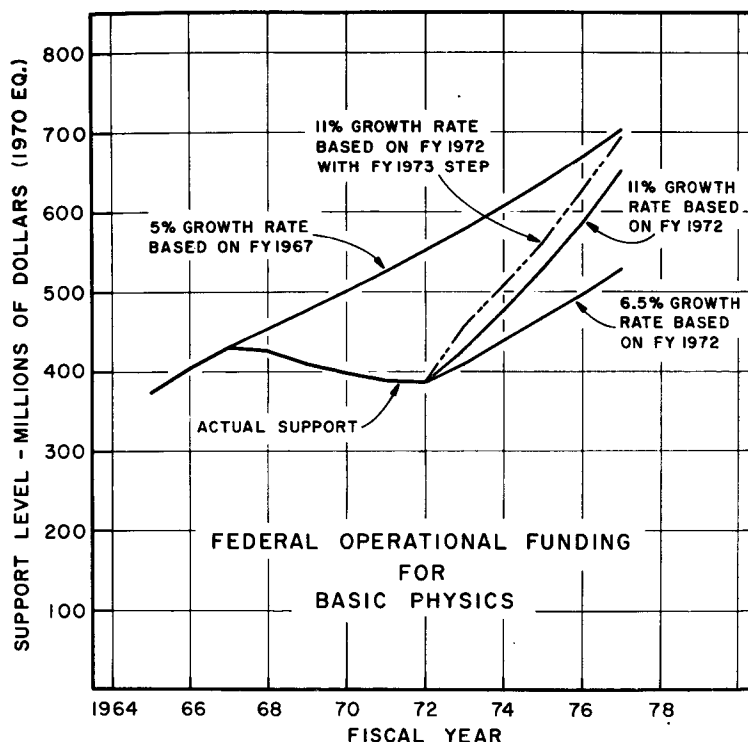


FIGURE 3 Total federal support for basic physics; actual expenditures for FY 1965 through FY 1972 with projections through FY 1977. Also shown for comparison is a 5 percent projection based on FY 1967.

cent per annum will not bring physics to the level that it would have reached had the modest 5 percent annual increase established in the early 1960's been maintained beyond fiscal year 1967 (even with the inclusion of certain fiscal year 1973 step increases discussed below). The 11 percent growth rate during this period will pay handsome dividends to society in both the long and the short range. Detailed projections beyond 1977 have not been attempted, since physics and its opportunities change so rapidly that such an attempt would be largely pointless.

Long before 1977 there will be changes of which the Committee has no present indication, and it will be necessary to maintain a continuing watch and re-evaluation of the appropriate projected growth rates. With a healthy economy, it appears that a new effective growth rate of 5 percent per annum over an extended period would be a reasonable one for science and for physics. The present 11 percent exploitation budget growth rate during the coming five years is an attempt to regain some of the ground lost to U.S. physics in the past five years. Thereafter a smooth transition to something more like the 5 percent figure or whatever other figure may be more appropriate to the needs and health of the national economy could be effected.

Reflecting the difficulties in long-range projection, the Committee has not attempted to detail the exact transition between the rebound growth rate and a more steady-state condition. Clearly this is one of the most important problems that must be addressed by both the physics community and the science policy components of the federal government within the next four years in the light of developments during the intervening period.

A Funding Level Floor

Can a minimum funding level be established below which substantial, severe damage would be done to the U.S. physics enterprise?

Again the situation in the heavily quantized fields of elementary-particle and nuclear physics, where the effects of budgetary reductions have been particularly severe and identifiable, are instructive. Under continuing level operating budgets (in dollars of constant value) the consequences would indeed be severe. By 1977 such operating budgets would reduce the effective SMY numbers in the two fields by about 22 percent and 30 percent, respectively, and would have already removed both fields from many important areas of research in any internationally competitive sense. Operating budgets declining at the rate of 6 percent per annum (documentation will be found in the respective panel reports of Volume II) would by 1977 force termination of large segments of the U.S. enterprise in both fields. U.S. aspirations, as sug-

gested elsewhere in this report, would be reduced to a qualitatively different level. Instead of working at the forefront of these fields and participating in many new discoveries, the physics community would be reduced to holding together the best possible response capability so that it would be able to understand the new discoveries made elsewhere and use them for the benefit of U.S. society.

The impact on the other subfields would be almost equally great despite their greater flexibility. One of the important components of this would be the demoralization of the field and the dismantling and dispersal of important and able research groups that have been developed and that even now are being held together in many cases by the most stringent of emergency measures. Once dispersed, these groups simply could not be reconstituted in anything less than a period of years; frequently they could *never* be reconstituted, as the members would take up other individual opportunities.

It should be emphasized, too, that in the past five years, following upon the growth period of the 1960's, there has been a continued period of belt tightening, of readjustment, and, more important, of development of emergency measures based on the hope that difficulties were temporary. These cannot continue any longer without permanent damage.

It is important to note here that in assessing the support of research in physics the tendency has been to talk about *total* support, including indirect costs and fringe benefits. When support was growing, direct costs tended to remain fairly nearly proportional to total costs and indirect costs rates remained reasonably constant. Since the period of declining budgets began, direct costs have been falling considerably faster than total costs. There is also considerable inertia built into indirect costs because many of them represent long-term commitments based on a certain size enterprise. In general, when the federal agencies have a fixed amount of money and indirect cost rates go up, the investigator has no choice but to reduce direct charges in order to accommodate the increased university overhead rate. The consequence of this is that the direct cost base on which overhead charges for the following year are calculated has been overestimated each year of declining budgets, with the result that the indirect cost escalates in the following year. Should present trends continue, the effect on the direct cost base could be disastrous.

For all these reasons, the Committee believes that it would be abdicating its responsibilities were it not to make the strongest possible case that the nation cannot afford to allow the effective support of physics to continue to decrease. Thus the level funding situation is regarded as a minimal floor below which U.S. activities in physics would no longer be in any sense competitive and would be totally inadequate to the role it

has long played as a source of technology, as a fundamental basis for and stimulator of other sciences, and as a vital component of education.

High-Leverage Situations

Small changes in funding—either up or down—can sometimes be reflected in large changes in scientific productivity. This concept of leverage is discussed more in Chapter 5. In the case of major facilities, such a large fraction of the total funding is required to keep them in operation that even small fractional changes in funding are reflected as very large changes in the research component, to which scientific productivity is much more directly coupled. In fields where new breakthroughs, either in concepts or in instrumentation, have occurred, new frontiers are opened, and investment in research at those frontiers can be expected to yield high scientific return. In other fields, again because of breakthroughs in instrumentation or ideas or because the field itself in its internal development has reached a state where further investment can be expected to yield returns of high societal importance, the leverage is high.

The relative weighting or importance assigned to each of these types of leverage will vary from field to field and from one support agency to another. This is healthy and proper. In examining program elements as candidates for high-leverage consideration, structural criteria play an important role. It is here, for example, that continuity considerations enter explicitly.

As illustrations of various types of high-leverage situations and the utilization of our Committee ordered listings, in combination with the subfield panel reports, the Committee selected from the subfields, 15 program elements the growth potentials of which warrant high priority for their support in the next five years. These are arbitrarily presented in an order that reflects the PhD manpower employed in the various subfields of physics—e.g., condensed matter employs the greatest number of PhD physicists, astrophysics and relativity the fewest.

It should be emphasized that the increased support recommended for these program elements should not be at the expense of other activities in the subfields, although clearly some readjustment is not only necessary but healthy as the various program elements attain different levels of scientific maturity. At the same time, it should be recognized that should only the selected program elements be supported, the overall physics research program would be totally unbalanced.

Macroscopic Quantum Phenomena

This topic includes superfluidity and superconductivity. With the development of a comprehensive theory of macroscopic quantum phenomena in solids and liquids, this area has attracted renewed activity

because of its intrinsic interest and its insight into the behavior of a many-body system—one of the central open problems in basic physics with broad applications in many other subfields. There is also important potential for utilization of these phenomena in such areas as low-loss power transmission in superconducting transmission lines, rapid transportation using magnetic levitation, and very compact, high-efficiency motors. Measurements on large-scale superconducting systems, until now primarily associated with possible new accelerator designs, have revealed unexpected questions and problems. This is a situation in which increased activity can bring high returns, both applied and fundamental.

Quantum Optics

This area is closely related to that of lasers and masers and shares similar advantages and potentials. Those aspects of the field that are peculiar to condensed matter, however, hold high promise of very important new applications in miniaturized devices, extraordinarily wide-band communications, and high-speed computers, to cite only a few obvious examples. This again is entirely apart from the fundamental new insights already gained—and to be gained—from investigations of the basic structure of both solids and liquids.

Scattering Studies on Solids and Liquids

Here are grouped several of the program elements of condensed-matter physics—studies involving scattering of neutrons, photons, and phonons in liquids and solids. New techniques and more intense sources have opened up entirely new ranges of phenomena, and recent progress toward understanding microscopic short- and long-range order in condensed matter has been rapid.

In Europe this field is regarded as of prime importance and promise. A \$95 million Franco-German facility devoted primarily to slow neutron interaction with condensed matter is about to begin operation in Grenoble. Although this field originated in the United States, unless drastic action is taken, supremacy will pass to Europe within the next five to ten years.

Heavy-Ion Interactions

Internationally this part of nuclear physics is attracting the greatest interest, effort, and support. Involving the interactions of large pieces of nuclear matter this field makes accessible, for the first time, entirely new modes of nuclear motion and dynamics and permits study of more familiar phenomena in entirely new regions of angular momentum and other parameters. It also makes accessible new nuclear species—both through moving away from the nuclear valley of stability to isotopes as yet unknown and upward along this valley to possible new supertransuranic elements. Quite apart from the very great intrinsic interest in these new areas, there are very important potential applications for these new species in medicine, in power generation, and in national

defense. Initiated in the United States, this field is being pursued vigorously by the Soviet Union, Germany, France, and other western European countries and indeed in all the major nuclear centers around the world with a wide variety of major accelerator facilities newly under construction. Unless a national facility of equivalent capability can be established soon, the United States will cease to have a significant role in this important field.

*Higher-Energy
Nuclear
Physics*

In a very real sense the detailed microscopic study of the nucleus, up to the present, has focused on the behavior of the outer nucleons. Although extrapolation of these surface findings deep into the nuclear interior has provided very useful insight into many nuclear phenomena, until quite recently the nuclear interior has not been accessible to careful experimental scrutiny. Similarly, measurements in the past at typically available energies have not been able to provide unambiguous information on the very-short-range behavior of the fundamental nucleon-nucleon interaction or on the importance of three-body or more complex possible interactions. With new facilities, typified by the Los Alamos Meson Physics Facility but also by such facilities as the Brookhaven AGS, these phenomena can be subjected to critical study. They are of fundamental importance to the further understanding of nuclear phenomena. So also are the experiments in which new secondary meson and hyperon probes are used to study nuclear systems.

*The National
Accelerator
Laboratory
and
Its Program*

As the world's most powerful proton accelerator, this facility truly represents a frontier salient in man's understanding of the ultimate structure of matter. It holds high promise of discovering fundamentally new aspects of nature that can have ramifications throughout science. It represents a cutting edge of science and has attracted the talents of some of the world's most distinguished physicists. Although the coupling to more extrinsic sciences and with technology is still relatively remote, it would be shortsighted indeed to conclude that such coupling cannot lie in the future.

*The Stanford
Linear
Accelerator
and
Its Program*

This facility is the world's most powerful electromagnetic probe for study of the structure of matter and is complementary to the National Accelerator Laboratory with its strongly interacting proton beams. During the past year it has been forced to operate at substantially below full research capability and, indeed, was closed down for two months to keep costs within available funds. Reflecting the very high leverage factors inherent in any such facility, even small fractional increases in funding will have disproportionately large returns in terms of research

productivity, effective utilization of highly trained manpower, and the major investment that has already been made in this accelerator and its extensive ancillary instrumentation. It provides one of the most promising windows into totally unknown realms of natural phenomena.

Controlled Fusion

In view of impressive recent progress, this field warrants greatly increased support. It holds high promise for the development of a new power source with reduced undesirable side effects. With an expected minimal impact on the environment and an inexhaustible fuel supply, availability of fusion power would have enormous beneficial consequences for man everywhere. A major commitment to the achievement of economic fusion power at the earliest date consistent with the orderly progress of the research and development activity in the field is fully justified. (See also Chapter 2.) Again, this is a highly competitive field in which the United States and the Soviet Union are major contenders. Without increased support it will be difficult, if not impossible, for the United States to maintain a competitive position or even to take advantage of developments elsewhere.

Turbulence

This is an area of extreme complexity and difficulty but one of corresponding great importance in all areas involving fluid flow. The subject has an impressive range from global circulation problems in meteorology and oceanography, through phenomena involved in supersonic flight and shock-tube phenomena, to the flow of blood in human circulatory systems. The present level of activity in this area is relatively low. Because of its very broad range of potential applications, both in and outside of science, increased activity could bring impressive returns.

Nonlinear Optics

This is an area of high leverage because it can provide an effective interface between atomic and molecular physics, condensed-matter physics, and major areas of technology. In addition, it has its own intrinsic potential for progress and new developments. It is important to emphasize, too, the extent to which this work in optics and that in the other areas of quantum optics and laser phenomena are symbiotic, with major progress in one frequently opening up opportunities for equivalent progress in the others. Applications from work in this area have only begun, and increased activity holds high promise of both extrinsic and intrinsic rewards.

Lasers and Masers

Quite apart from the fundamental new physics intrinsic in these devices themselves and their underlying theoretical understanding, applications and implications of studies of lasers and masers have been remarkably pervasive throughout much of science and technology—and in fields as

far removed as medicine and the fine arts. The exploitation of these new devices has only begun.

*Atomic
and
Molecular
Beam Studies*

Here research has undergone a renaissance, reflecting the fact that the so-called atomic or chemical accelerators have recently become available and can provide beams of atomic and molecular species at the electron-volt energies of interest to atomic physics, to chemistry, and to biology. This makes possible the transfer of a large body of techniques, both experimental and theoretical, from nuclear and particle physics relating to the study of elementary quantum collisions and interactions. Studies hold high promise for providing fundamental information on molecular structure and on the basic mechanisms whereby atomic and molecular species interact. From a practical viewpoint, this puts the understanding of chemical reaction mechanisms on an entirely new and more fundamental basis, with great potential return. It also can provide vital insights into mechanisms of major interest to molecular biology.

*Biophysical
Acoustics*

As in the preceding program element, recent progress in biophysical acoustics has yielded new fundamental understanding of the physics involved in speech and hearing functions. Here again, increased activity holds high promise of alleviating a wide variety of incapacitating human ills within a relatively short time. Research in this area has drawn on a very wide variety of techniques from other disciplines of physics ranging from the Mössbauer effect from nuclear physics in measuring microscopic motions of the components of the inner ear to the use of miniaturized, implanted solid-state transducers and precision optical interferometric devices. It provides an excellent example of the application of such techniques to biophysical problems. As physics, the field is still small; but it is of growing significance, and the future potential is large.

*Very Large
Radio
Receiving
Array*

We concur in the conclusion of the Astronomy Survey Committee that the provision of very large radio telescope receiving arrays holds high promise of major new discoveries concerning the structure of the universe.* Most of the recent astonishing discoveries in astrophysics—quasars, pulsars, cosmic background radiation, interstellar masers—were made by radio telescopes. To exploit these discoveries, a major new instrument capable of producing sharp images of the radio sky is needed. A receiving array, which produces an image as sharp as that of the 200-in. optical telescope (1 sec of arc) by means of a principle known as “aperture synthesis,” can be built for \$62 million. This instrument would be far superior to any available for many years to come. A three-antenna

**Astronomy and Astrophysics for the 1970's* (National Academy of Sciences, Washington, D.C., 1972).

prototype of the system (which would consist of 27 individual antennas) has been built and has demonstrated its power to distinguish powerful quasars at the very limits of the observable universe and to produce sharp pictures of nearby exploding stars and galaxies. To continue the intensive study of such objects in the decade ahead, it is essential that a large array be built if U.S. radio astronomers, now doing excellent competitive work with present instruments, are to participate in the exciting discoveries certain to be made, if not in the United States, by instruments now under construction overseas.

*X-Ray and
Gamma-Ray
Astronomy*

The Survey Committee again concurs with the recommendation of the Astronomy Survey Committee that the High Energy Astronomical Observatory (HEAO) also should be an important part of the national effort in astrophysics and astronomy.* Because of the opaqueness of the earth's atmosphere to both x and gamma radiation, these windows to the universe have only very recently been opened through the use of rocket and satellites. Any reasonable extrapolation from the preliminary soundings obtained thus far suggests a very large return in fundamental insight into the structure and history of the universe. In terms of the scope of the total national physics program, the estimated cost of this facility—\$400 million—is extremely high. To be considered in proper context it must be viewed within the perspective of the total expenditures in the U.S. space program. In terms of anticipated scientific return—both short and long range—it merits high priority in that program.

Program emphases at one overall level of funding may be quite different from that at another. The instinct for survival takes precedence over any objectively evolved, balanced program when the necessity for such consideration is forced upon any field. We would not recommend that it be otherwise. However, it is vitally important that even in the least favorable of situations the nation retain a rebound capability so that with an improved economy the scientific enterprise remains viable and can re-expand without unavoidable delay, to address again the available opportunities at whatever level of effort the overall play of political processes may make possible. In view of the increasingly tight coupling between the health of the nation's scientific and technological enterprise and the national economy, particularly in times of a depressed economy, any direct coupling of the support of this enterprise to the economy could have elements of disaster. Illustrative of this point is the experience of the General Electric Company, which made the corporate deci-

**Astronomy and Astrophysics for the 1970's* (National Academy of Sciences, Washington, D.C., 1972).

sion during the economic depression in the early 1930's to avoid drastic cutback in its research and developmental activities, a step all too commonly taken by other companies. The result was that, when the economy rebounded, General Electric had a backlog of new ideas, new devices, and an internal strength in terms of experienced and dedicated manpower that has played a very significant role in the attainment of the competitive position that this company now enjoys.

CONCLUSION

Because of all the foregoing considerations, the Committee has not attempted to detail any specific national program for physics in the next five-year period in the range between the exploitation (11 percent growth) and flat (0 percent growth) levels of investment—both in dollars of constant purchasing power. Within each subfield, to the extent to which the subfield panels have found it possible, this detailing has been carried out (Volume II). It has been more feasible in some subfields than in others.

The fact that we do not recommend a detailed national physics program appropriate to different possible levels of funding does not reflect any unwillingness to face the difficulties inherent in any such attempt. Rather it reflects the conclusion that it is impossible for any group such as the Physics Survey Committee to develop either the adequately complete information or insight necessary to make such a detailed attempt meaningful. It is unrealistic to look upon the total funding of U.S. physics as an effective reservoir from which funding for individual program elements is parceled out without having cognizance of all the internal and external pressures and constraints within both the different funding agencies and the physics community itself. These, moreover, change rapidly with the magnitude of the overall funding available. Any system of funding for science must allow for a considerable degree of initiative and new directions originating at the working level. An *a priori* allocation system, which parcels out a fixed amount of total funding among predefined fields of science, is likely to be stultifying of initiative and novelty.

The subfield panel reports provide a detailed discussion of opportunities and needs viewed primarily in terms of intrinsic and structural criteria internal to the subfields themselves. The Committee attempted to view the program elements of these subfields within a broader context including more explicit extrinsic criteria. In testing and refining these criteria and as an illustration of their use, the Committee carried out a detailed jury rating of the program elements in terms of the intrinsic and extrinsic criteria. The result was a series of ordered listings of the program elements weighting the different classes of criteria in dif-

ferent fashion. These listings may be of interest as reflecting the consensus of the Survey Committee, but it should again be emphasized that relative ordering in any restricted section of these listings is not to be considered as significant.

It is hoped that this illustrated approach to a more general evaluation of the program elements in physics taken together with the more detailed support documentation in the subfield panel reports will form a major input to the development of program emphases in terms of the level of funding that can be provided.

As discussed, there are two particularly urgent situations (the Los Alamos Meson Physics Facility and the National Accelerator Laboratory) that must be addressed in fiscal year 1973. In addition, there are some 15 program elements that hold promise of unusual productivity with increased support in the period through fiscal year 1977.

PROGRAM ELEMENTS

In the following tables, subfields of physics have been divided into "program elements" (major research areas). Although the definition of this term is somewhat imprecise, the intent has been to identify separable components of the subfields—components sufficiently large to have some internal coherence and reasonable boundaries and for which it might be possible to estimate present funding levels and the PhD manpower involved. As discussed in this chapter, the purpose of this exercise was to divide the subfields into units of activity that the Committee could rate in terms of intrinsic, extrinsic, and structural criteria. The purpose of the ratings was to test the feasibility of arriving at a consensus regarding the desirable relative emphasis among subfields and among program elements within each subfield.

Data available to the Committee permitted identification of program elements, at least roughly, for all subfields except earth and planetary physics. In some cases the program elements cover the major activities in the subfield; in others they do not. It should be noted that much of the work in such subfields as optics and acoustics lies largely outside physics, and that the basic physics research in some of the program elements involves only a small part of the total dollars and manpower associated with the subfield.

Clearly, most of the program elements could be further subdivided, but, to keep the overall number for the Committee's consideration within manageable limits, the number per subfield was somewhat arbitrarily restricted to about ten. As expected, the subfield panels found it convenient to make the divisions into program elements along different lines. For example, in elementary-particle physics the division is made in

terms of the small number of major facilities and associated programs, whereas in condensed matter the division accents specific areas of research such as superconductivity. The program elements for astrophysics and relativity identify emerging areas of research that will require greatly increased funding. In the projected program for this subfield, the costs of satellites and large facilities are included. Funding figures associated with program elements in the other subfields do not include construction costs of major facilities.

In developing these program elements the Committee worked with the panel chairmen; however, in some cases the elements used here are not identical with those suggested by the panel chairmen. In elementary-particle physics and nuclear physics it was possible to assign funding levels and manpower rather precisely. Similar assignments for some of the program elements in the other subfields may be in error by a factor of two.

Listed in Order of Overall Scoring

PROGRAM ELEMENT	PHYSICS SUBFIELD
1. Lasers and masers	Atomic, molecular, and electron
2. National Accelerator Laboratory	Elementary-particle
3. Quantum optics	Condensed matter
4. University groups—EPP	Elementary-particle
5. Stanford Linear Accelerator	Elementary-particle
6. Nuclear dynamics	Nuclear
7. Major facilities—EPP, AGS improvement, etc.	Elementary-particle
8. Brookhaven AGS	Elementary-particle
9. Nuclear excitations	Nuclear
10. Heavy-ion interactions	Nuclear
11. Higher-energy nuclear physics	Nuclear
12. Nuclear astrophysics	Nuclear
13. Theoretical relativistic astrophysics	Astrophysics and relativity
14. Neutron physics	Nuclear
15. Nuclear theory	Nuclear
16. Very large radio arrays*	Astrophysics and relativity
17. X- and gamma-ray observatory*	Astrophysics and relativity
18. Turbulence in fluid dynamics	Plasma and fluids
19. Superfluidity	Condensed-matter
20. Infrared astronomy*	Astrophysics and relativity
21. General relativity tests	Astrophysics and relativity
22. Oceanography*	Plasma and fluids
23. Atomic and molecular beams	Atomic, molecular, and electron
24. Laser-related light sources	Optics
25. Controlled fusion	Plasma and fluids
26. Digitized imaging devices for optical astronomy	Astrophysics and relativity

PROGRAM ELEMENT	PHYSICS SUBFIELD
27. Surface physics	Condensed-matter
28. Gravitational radiation	Astrophysics and relativity
29. Aperture synthesis for infrared astronomy	Astrophysics and relativity
30. Nonlinear optics	Optics
31. Argonne ZGS	Elementary-particle
32. Magnetic properties of solids	Condensed-matter
33. Semiconductors	Condensed-matter
34. Gamma-ray detectors in astronomy	Astrophysics and relativity
35. Electronic properties of solids and liquids	Condensed matter
36. Holography and information storage	Optics
37. Hearing, speech, and biophysical acoustics	Acoustics
38. CEA Bypass Storage Ring	Elementary-particle physics
39. High magnetic fluids	Condensed-matter
40. Cornell Synchrotron	Elementary-particle
41. Laboratory astrophysics, and fluids	Plasma and fluids
42. Neutrino astronomy	Astrophysics and relativity
43. Nuclear facilities and instrumentation	Nuclear
44. Electron physics	Atomic, molecular, and electron
45. Computer modeling	Plasma and fluids
46. MHD power generation	Plasma and fluids
47. Turbulent plasmas	Plasma and fluids
48. Optical band communication	Optics
49. Fluid and plasma dynamics and lasers	Plasma and fluids
50. Nonelectronic aspects of solids and liquids	Condensed-matter
51. Nuclear decay studies	Nuclear
52. Weak and electromagnetic interactions	Nuclear
53. Optical systems and lens designs, etc.	Optics
54. Luminescence, etc.	Condensed-matter
55. Optical information processing	Optics
56. Berkeley Bevatron	Elementary-particle
57. Atomic and molecular spectroscopy	Atomic, molecular, and electron
58. Integrated optics	Optics
59. Meteorology*	Plasma and fluids
60. Metrology*	Optics
61. Accelerator development	Elementary-particle
62. Gas discharges	Atomic, molecular, and electron
63. Crystallography, etc.*	Condensed-matter
64. Electroacoustics and acoustics instrumentation	Acoustics
65. Slow neutron physics	Condensed-matter
66. Ultrasonics and infrasonics	Acoustics
67. Underwater sound	Acoustics
68. Noise, mechanical shock and vibration	Acoustics
69. Music and architectural acoustics*	Acoustics

*These program elements involve large funding and activity in adjacent sciences; in this Survey attention has been focused on the physics component of each.

Listed in Order of Extrinsic Scoring

PROGRAM ELEMENT	PHYSICS SUBFIELD
1. Lasers and masers	Atomic, molecular, and electron
2. Quantum optics	Condensed-matter
3. Nuclear excitations	Nuclear
4. Controlled fusion	Plasma and fluids
5. Nuclear dynamics	Nuclear
6. Oceanography*	Plasma and fluids
7. Laser-related light sources	Optics
8. Neutron physics	Nuclear
9. Surface physics	Condensed-matter
10. Computer modeling	Plasma and fluids
11. MHD power generation	Plasma and fluids
12. Semiconductors	Condensed-matter
13. Holography and information storage	Optics
14. Turbulence in fluid dynamics	Plasma and fluids
15. Optical band communication	Optics
16. Magnetic properties of solids	Condensed-matter
17. Meteorology*	Plasma and fluids
18. Electronic properties of solids and liquids	Condensed-matter
19. Fluid and plasma dynamics and lasers	Plasma and fluids
20. Hearing, speech, and biophysical acoustics	Acoustics
21. Metrology*	Optics
22. Nuclear facilities and instrumentation	Nuclear
23. Optical information processing	Optics
24. Electroacoustics and acoustics instrumentation	Acoustics
25. Optical system and lens design	Optics
26. Electron physics	Condensed-matter
27. Noise, mechanical shock, and vibration	Acoustics
28. Ultrasonics and infrasonics	Acoustics
29. Laboratory astrophysics, plasma and fluids	Plasma and fluids
30. Underwater sound	Acoustics
31. Nonelectronic aspects of solids and liquids	Condensed-matter
32. Gas discharges	Atomic, molecular, and electron
33. Nonlinear optics	Optics
34. Heavy-ion interactions	Nuclear
35. Luminescence, etc.	Condensed-matter
36. Atomic and molecular beams	Atomic, molecular, and electron
37. Crystallography, etc.*	Condensed-matter
38. High magnetic fields	Condensed-matter
39. Integrated optics	Optics
40. Turbulent plasmas	Plasma and fluids
41. Nuclear decay studies	Nuclear
42. Music and architectural acoustics*	Acoustics
43. Superfluidity	Condensed-matter
44. Higher-energy nuclear physics	nuclear

PROGRAM ELEMENT	PHYSICS SUBFIELD
45. Accelerator development	Elementary-particle
46. Atomic and molecular spectroscopy	Atomic, molecular, and electron
47. National Accelerator Laboratory	Elementary-particle
48. Nuclear theory	Nuclear
49. Infrared astronomy*	Astrophysics and relativity
50. Major facilities—EPP	Elementary-particle
51. Digital imaging devices for optical astronomy	Astrophysics and relativity
52. Stanford Linear Accelerator	Elementary-particle
53. Very large radio array*	Astrophysics and relativity
54. Gamma-ray detectors in astronomy	Astrophysics and relativity
55. Brookhaven A G S	Elementary-particle
56. Weak and electromagnetic interaction	Nuclear
57. X- and gamma-ray astronomy*	Astrophysics and relativity
58. University groups—EPP	Elementary-particle
59. Nuclear astrophysics	Nuclear
60. Theoretical relativistic astrophysics	Astrophysics and relativity
61. CEA Bypass Storage Ring	Elementary-particle
62. Argonne Z G A	Elementary-particle
63. Aperture synthesis for infrared astronomy	Astrophysics and relativity
64. Cornell Synchrotron	Elementary-particle
65. Gravitational radiation	Astrophysics and relativity
66. Neutrino astronomy	Astrophysics and relativity
67. General relativity tests	Astrophysics and relativity
68. Berkeley Bevatron	Elementary-particle
69. Slow neutron physics	Condensed-matter

*These program elements involve large funding and activity in adjacent sciences; in this Survey attention has been focused on the physics component of each.

Listed in Order of Intrinsic Scoring

PROGRAM ELEMENT	PHYSICS SUBFIELD
1. National Accelerator Laboratory	Elementary-particle
2. University groups—EPP	Elementary-particle
3. Stanford Linear Accelerator	Elementary-particle
4. Brookhaven A G S	Elementary-particle
5. Major facilities—EPP	Elementary-particle
6. General relativity tests	Astrophysics and relativity
7. Nuclear astrophysics	Nuclear
8. Theoretical relativistic astrophysics	Astrophysics and relativity
9. X- and gamma-ray astronomy*	Astrophysics and relativity
10. Lasers and masers	Atomic, molecular, and electron
11. Very large radio array*	Astrophysics and relativity
12. Higher-energy nuclear physics	Nuclear
13. Nuclear theory	Nuclear
14. Gravitational radiation	Astrophysics and relativity

PROGRAM ELEMENT	PHYSICS SUBFIELD
15. Argonne ZGS	Elementary-particle
16. Infrared astronomy*	Astrophysics and relativity
17. Aperture synthesis for infrared astronomy	Astrophysics and relativity
18. Heavy-ion interactions	Nuclear
19. Digitized imaging devices for optical astronomy	Astrophysics and relativity
20. Superfluidity	Condensed-matter
21. Neutrino astronomy	Astrophysics and relativity
22. CEA Bypass Storage Ring	Elementary-particle
23. Cornell Synchrotron	Elementary-particle
24. Gamma-ray detectors in astronomy	Astrophysics and relativity
25. Quantum optics	Condensed-matter
26. Atomic and molecular beams	Atomic, molecular, and electron
27. Berkeley Bevatron	Elementary-particle
28. Nuclear dynamics	Nuclear
29. Turbulence in fluid dynamics	Plasma and fluids
30. Nonlinear optics	Optics
31. Nuclear excitations	Nuclear
32. Weak and electromagnetic interactions	Nuclear
33. High magnetic fields	Condensed-matter
34. Neutron physics	Nuclear
35. Hearing, speech, and biophysical acoustics	Acoustics
36. Slow neutron physics	Condensed-matter
37. Magnetic properties of solids	Condensed-matter
38. Turbulent plasmas	Plasma and fluids
39. Laboratory astrophysics, plasma and fluids	Astrophysics and relativity
40. Electronic properties of solids and liquids	Condensed-matter
41. Oceanography*	Plasma and fluids
42. Surface physics	Condensed-matter
43. Laser-related light sources	Optics
44. Semiconductors	Condensed-matter
45. Electron physics	Atomic, molecular, and electron
46. Nuclear-decay studies	Nuclear
47. Nuclear facilities and instrumentation	Nuclear
48. Atomic and molecular spectroscopy	Atomic, molecular, and electron
49. Controlled fusion	Plasma and fluids
50. Holography and information storage	Optics
51. Nonelectronic aspects of solids and liquids	Condensed-matter
52. Integrated optics	Optics
53. Luminescence, etc.	Condensed-matter
54. Accelerator development	Elementary-particle
55. Fluid and plasma dynamics and lasers	Plasma and fluids
56. Optical band communication	Optics
57. Optical system and lens design	Optics
58. Computer modeling	Plasma and fluids
59. MHD power generation	Plasma and fluids

PROGRAM ELEMENT	PHYSICS SUBFIELD
60. Optical information processing	Optics
61. Meteorology*	Plasma and fluids
62. Crystallography, etc.*	Condensed-matter
63. Gas discharges	Atomic, molecular, and electron
64. Metrology*	Optics
65. Electroacoustics and acoustics instrumentation	Acoustics
66. Ultrasonics and infrasonics	Acoustics
67. Underwater sound	Acoustics
68. Music and architectural acoustics	Acoustics
69. Noise, mechanical shock, and vibration	Acoustics

*These program elements involve large funding and activity in adjacent sciences; in this Survey attention has been focused on the physics component of each.

Extrinsic/Intrinsic Ratio

PROGRAM ELEMENT	PHYSICS SUBFIELD
1. Noise, mechanical shock, and vibration	Acoustics
2. Underwater sound	Acoustics
3. Music and architectural acoustics	Acoustics
4. Ultrasonics and infrasonics	Acoustics
5. Electroacoustics and acoustics instrumentation	Acoustics
6. Metrology*	Optics
7. Meteorology*	Plasma and fluids
8. Computer modeling	Plasma and fluids
9. MHD power generation	Plasma and fluids
10. Gas discharges	Atomic, molecular, and electron
11. Crystallography, etc.*	Condensed-matter
12. Optical band communication	Optics
13. Optical information processing	Optics
14. Controlled fusion	Plasma and fluids
15. Fluid and plasma dynamics and lasers	Plasma and fluids
16. Optical system and lens design	Optics
17. Surface physics	Condensed-matter
18. Laser-related light sources	Optics
19. Oceanography*	Plasma and fluids
20. Holography and information storage	Optics
21. Neutron physics	Nuclear-physics
22. Nuclear facilities and instrumentation	Nuclear-physics
23. Nonelectronic aspects of solids and liquids	Condensed-matter
24. Nuclear excitations	Nuclear-physics
25. Semiconductors	Condensed-matter
26. Electronic properties of solids and liquids	Condensed-matter
27. Magnetic properties of solids	Condensed-matter
28. Integrated optics	Optics

PROGRAM ELEMENT	PHYSICS SUBFIELD
29. Luminescence, etc.	Condensed-matter
30. Electron physics	Atomic, molecular, and electron
31. Quantum optics	Condensed-matter
32. Laboratory astrophysics, plasma and fluids	Astrophysics and relativity
33. Hearing, speech, and biophysical acoustics	Acoustics
34. Accelerator development	Elementary-particle
35. Nuclear dynamics	Nuclear
36. Lasers and masers	Atomic, molecular, and electron
37. Turbulence in fluid dynamics	Plasma and fluids
38. Nuclear decay studies	Nuclear
39. Turbulent plasmas	Plasma and fluids
40. High magnetic fields	Condensed-matter
41. Atomic and molecular spectroscopy	Atomic, molecular, and electron
42. Nonlinear optics	Optics
43. Atomic and molecular beams	Atomic, molecular, and electron
44. Heavy-ion interactions	Nuclear
45. Weak and electromagnetic interactions	Nuclear
46. Superfluidity	Condensed-matter
47. Higher-energy nuclear physics	Nuclear
48. Nuclear theory	Nuclear
49. Infrared astronomy*	Astrophysics and relativity
50. Digitized imaging devices for optical astronomy	Astrophysics and relativity
51. Gamma-ray detectors in astronomy	Astrophysics and relativity
52. Very large radio array*	Astrophysics and relativity
53. Aperture synthesis for infrared astronomy	Astrophysics and relativity
54. Slow neutron physics	Condensed-matter
55. National Accelerator Laboratory	Elementary-particle
56. Stanford Linear Accelerator	Elementary-particle
57. Brookhaven AGS	Elementary-particle
58. Major facilities—EPP	Elementary-particle
59. X- and gamma-ray observatory*	Astrophysics and relativity
60. Gravitational radiation	Astrophysics and relativity
61. Argonne ZGS	Elementary-particle
62. Neutrino astronomy	Astrophysics and relativity
63. CEA Bypass Storage Ring	Elementary-particle
64. Cornell synchrotron	Elementary-particle
65. Berkeley Bevatron	Elementary-particle
66. University groups—EPP	Elementary-particle
67. Nuclear astrophysics	Nuclear
68. Theoretical relativistic astrophysics	Astrophysics and relativity
69. General relativity tests	Astrophysics and relativity

*These program elements involve large funding and activity in adjacent sciences; in this Survey attention has been focused on the physics component of each.

Funding and Manpower

ELEMENTARY-PARTICLE PHYSICS (1971)

PROGRAM ELEMENTS	FEDERAL SUPPORT (\$ Millions) ¹	PhD MANPOWER ²
1. Accelerator developments	3.6	— ³
2. National Accelerator Laboratory	— ⁴	
3. Other major facilities (e.g., A G S improvement project)	1.5	— ³
4. Stanford Linear Accelerator	27	99
5. Brookhaven A G S	27	99
6. Argonne Z G S	20	65
7. Berkeley Bevatron	26	100
8. Cornell Synchrotron	3	20
9. CEA Bypass Storage Ring	2.3	11
10. University groups	37	1245 ⁵

¹ Construction costs not included.

² Includes approximately 300 scientists having the following specialties or combinations of them: computer employment in research, accelerator design and development, accelerator operation, device design and development, and emulsion experiments.

³ Manpower included in elements 4 to 9.

⁴ No NAL figures are given for FY 1971 since the accelerator will not be in operation until FY 1972.

⁵ Includes approximately 245 PhD's doing particle research but not supported directly by federal funds. Nonfederal support estimated to be of the order of 5 percent of total federal funding.

Description of Program Elements

1. These activities are an integral part of the ongoing work at each of the major accelerator laboratories. They have a creative content quite apart from the particle research itself, although neither can progress without the other. The technological requirements lead to innovation and development in such fields as radiofrequency engineering, superconducting magnets, ultra-fast electronics, computer technology, radiation detection instruments, pattern recognition, and particle orbit theory.

2. 200–500 GeV proton accelerator to be for some years the only controlled source of protons in the world for research* in the energy range above 80 GeV and the only one in the United States above 33 GeV. Also includes in-house research activities comprising a small fraction of the particle research to be carried out at the accelerator.

3. They are major additions to the capabilities of accelerators—other than NAL—that have been planned or under construction for some years and are now complete or nearing completion. Includes: the major modification of the A G S to increase its intensity and capabilities, the S P E A R storage ring at S L A C, and the 12-ft liquid hydrogen bubble chamber at the Z G S. Each facility offers unique opportunities to perform ground-breaking research but will require incremental operating and equipment funds for the purpose.

4. 22-GeV electron accelerator, which is the only controlled source of electrons in the world for research* in the energy range above 10 GeV. Also includes

in-house research activities comprising a substantial fraction (about one half) of the research carried out with this accelerator.

5. The 33-GeV proton accelerator at BNL, which is the principal source in the United States for research using protons in energy range 12–33 GeV. Includes in-house research comprising about 25 percent of the total research activity.

6. The 12.5-GeV accelerator at ANL, which is the principal source in the United States for research* using protons in the energy range 6–12 GeV. Includes in-house research effort comprising about 25 percent of the total research activity.

7. The 6-GeV proton accelerator at LRL, which is the principal source in the United States for research using protons in the energy range 1–6 GeV. Includes substantial in-house research activity.

8. A 10-GeV electron accelerator. This is a high-duty-cycle machine (in contrast to SLAC) for research* with electrons in the energy range 1–10 GeV. The in-house research activity is dominant, but there is potential for expansion to include more research by outside users.

9. A 6-GeV electron accelerator with a high duty cycle, which has recently been limited to activities associated with the development of a by-pass to serve as a storage ring to study the collisions of 3.5-GeV electrons and positrons. It is the only such facility presently available in the United States and is currently under test.

10. University research groups responsible for carrying out most of the experimental particle-physics research at the major accelerator laboratories. Includes activities of professors, postdocs, graduate students, and associated technical services required to provide electronics, detection equipment, data handling and analysis systems, etc. to the extent that these aspects of the research can be mounted at the universities. Includes both experimental and theoretical physicists.

*Each accelerator is a source of the indicated primary particles and many beams of secondary particles (pions, K-mesons, neutrinos, muons, antiprotons, hyperons, etc.).

NUCLEAR PHYSICS (FY 1969)

PROGRAM ELEMENTS ¹	FEDERAL SUPPORT (\$ Millions) ²	PhD MANPOWER ³
1. Nuclear excitation } 2. Nuclear dynamics }	33.7	695
3. Heavy-ion interactions	3.1	20
4. Higher-energy nuclear physics	7.9	95
5. Neutron physics	7.7	115
6. Nuclear decay studies	3.2	65
7. Weak and electromagnetic interactions	0.7	20
8. Nuclear facilities and instrumentation	3.8	50
9. Nuclear astrophysics	0.4	20
10. Nuclear theory	5.0	260

¹These program elements do not include all current basic research activities in nuclear physics supported by the federal government. Approximately 140 PhD's are working in such areas as data compilations and nuclear chemistry.

²Non-federal support estimated at 25-30 percent of federal support, on the average, in those projects supported by the federal agencies. Construction funds are not included.

³Another 300 PhD's are working either in applied nuclear physics or are supported entirely by non-federal funds.

Description of Program Elements

1. The study of the nuclear degrees of freedom with a broad spectrum of nuclear probes.
2. The study of the nature of nuclear reactions.
3. The study of the now largely unknown interactions between massive amounts of nuclear matter.
4. The study of nuclei with short-wavelength electron, proton, and mesonic probes.
5. The study of nuclear phenomena with a neutral strongly interacting probe.
6. The study of nuclear states via the decay of radioactive nuclei.
7. The study of fundamental symmetries in the nuclear domain.
8. The tools of nuclear physics.
9. Nuclear reactions of interest to astrophysics.
10. The theoretical aspects of all the above fields and their relations to the fundamental nuclear interactions.

ATOMIC, MOLECULAR, AND ELECTRON PHYSICS (1970)

PROGRAM ELEMENTS ¹	FEDERAL AND NONFEDERAL SUPPORT ¹ (\$ Millions)	ESTIMATED PhD MANPOWER ²
1. Gas discharge	1.6	35
2. Electron physics	4.0	80
3. Lasers and masers	5.0	100
4. Atomic and molecular spectroscopy	4.0	80
5. Atomic, ionic, and molecular beams	6.4	130

¹ A substantial amount of activity in these program elements is supported from sources outside the AME subfield, e.g., plasma physics, space and planetary physics, electrical engineering, and chemistry. If included, this may double most of the above numbers.

² Based on estimated level of activity and 1970 National Register data in which a total of 1065 PhD scientists identified with AME physics.

Definition of Program Elements

1. Gas discharge including low- and medium-density plasmas.
2. Electron physics including the low-energy electron diffraction technique, electron optics, electron-atom collisions, high-vacuum techniques, surface properties.
3. Lasers and masers including time and length standards, higher-order electromagnetic interactions, photon statistics, nonlinear spectroscopy, coherent x rays.
4. Atomic and molecular spectroscopy including positronium and muonium spectra, tests of quantum electrodynamics, optical pumping, vacuum uv, far infrared and radio spectroscopy.
5. Atomic, ionic, and molecular beams including colliding beams, beam-foil spectroscopy, highly excited molecules and atoms.

CONDENSED MATTER (1970)

PROGRAM ELEMENTS ¹	ESTIMATED FEDERAL AND NONFEDERAL SUPPORT (\$ Millions)	ESTIMATED PhD MANPOWER ²
1. Crystallography, etc.	9.0	150
2. Surface physics	20.5	340
3. Semiconductors	33.0	550
4. Nonelectronic aspects	18.5	310
5. Luminescence, etc.	9.5	190
6. Electronic properties of solid or molten metal	15.0	260
7. Magnetic properties	25.0	430
8. Quantum optics	9.0	150
9. High magnetic fields	3.5	60
10. Superfluidity	4.5	75
11. Slow neutron physics	8.5	75

¹These program elements do not include all current basic research activity in condensed-matter physics.

²Based on estimated level of activity and 1970 National Register data in which 4160 PhD scientists identified with condensed-matter physics.

Description of Program Elements

1. Structures of crystals, including studies of atomic arrangements by neutron, electron, and x-ray diffraction techniques.
2. Includes all the properties of surfaces and thin films, crystal growth from vapor or the melt, properties of solid-solid interfaces.
3. Includes all the electronic properties of nonmetallics with small bandgaps in their pure states and having appreciable conductivity in suitably doped states.
4. Includes all the properties of defects and dislocations in crystals that are usually described without invoking the quantum-mechanical behavior of atoms. Includes plasticity, rupture, internal friction, diffusion, ionic conduction, phonons, and lattice vibrations.
5. Includes band-structure calculations, optical properties, optical effects, and electronic levels of impurities and other information bearing on the electronic levels of insulating crystals.
6. Includes all the electrical and thermal conduction phenomena due to electrons, optical properties of metals, band-structure calculations, plasma oscillations, and superconductivity.
7. Includes electron paramagnetic and nuclear paramagnetic resonance work, studies of static magnetic susceptibilities, and all phenomena connected with ferromagnetism.
8. Includes lasers and masers, nonlinear optical effects, and other effects that can only be studied by laser light.
9. Experiments that are done in condensed matter with fields in excess of 120 kG.
10. Work with superfluid liquid helium.
11. Work requiring use of moderated neutrons from a pile.

OPTICS (1970)

PROGRAM ELEMENTS ¹	ESTIMATED FEDERAL AND NONFEDERAL SUPPORT (\$ Millions) ²	ESTIMATED Ph.D. MANPOWER (Physicists) ^{1,3}
1. Metrology	0.8	15
2. Optical information processing	0.9	17
3. Optical band communication	0.1	2
4. Optical systems lens design, etc.	2.2	40
5. Laser-related light sources	7.5	137
6. Holography and information storage	4.0	73
7. Integrated optics	0.6	11
8. Nonlinear optics	3.0	55

¹ These program elements do not include all areas of basic research in optics. It is estimated there are another 690 PhD physicists working in areas not included in these program elements.

² The average annual cost per PhD does not vary widely across the program elements and is estimated to be \$55,000/PhD.

³ These estimates do not represent the magnitude of the manpower effort in the various program elements. They represent a judgment on the number of personnel from the physics section of the National Register of Scientific and Technical Personnel and do not include the large effort made by engineers, which is uniformly and properly considered optics.

Description of Program Elements

1. Metrology is the science of measurement. With lasers, very precise measurements may be made of such things as the distance to the moon, the compression of the earth in earthquake zones, and the deformation of large structures. Useful new phenomena will certainly be discovered.

2. Optical information processing is used to reduce blur in photographs, to enhance contrast, smooth out grain, sharpen edges, etc. It is also possible to use optical techniques for automatic photointerpretation and character recognition.

3. Optical band communications is capable of transmitting tremendous amounts of information wherever a beam of light can be sent. Long-distance communication through glass fibers now seems possible with modulated laser beams.

4. Modern computers and system science have made it possible to design optical systems and instruments that are optimized. Very large improvements can be made, particularly when new laser sources and solid-state receivers are included in the design.

5. Lasers can be made to have extremely high energy or power or power density. Others have very precise and steady wavelength, and still others can be tuned to different wavelengths. Each new improvement makes new techniques possible and simplifies the solution of old problems.

6. Holography is a method of storing an image or other information in a photographic film by recording the interference pattern between the signal-carrying light and a coherent reference wave. It offers potential advantages over other compact storage methods for large amounts of information.

7. A beam of light can be trapped and guided in a thin film on a solid surface, rather like electricity in a wire. It can then be manipulated by acoustical, electrical, or other optical signals for computer logic, modulation, scanning, or signaling. The combination is called "integrated optics."

8. Some materials, when illuminated very intensely, give off light of doubled frequency. In other cases, two beams mixed in a crystal give light of several sum and difference frequencies. Knowledge can be gained about the material, and useful devices can be built.

ACOUSTICS (1971)

PROGRAM ELEMENTS	ESTIMATED FEDERAL AND NONFEDERAL SUPPORT (\$ Millions) ^{1,2}	ESTIMATED PhD MANPOWER ³
1. Noise, mechanical shock, and vibration	1.8	35
2. Underwater sound	4.9	90
3. Music and architecture	0.8	15
4. Ultrasonics and infrasonics	1.1	20
5. Electroacoustics and acoustic instrumentation	1.1	20
6. Hearing, speech, and biophysical acoustics	0.8	15

¹ Based on estimated level of activity of physicists doing basic research in acoustics that leads to publishable reports. Costs/PhD across the program elements is assumed to be \$55,000/year.

² Federal and industrial support of applied research in acoustics is estimated at \$50 million.

³ Based on estimated level of activity and 1970 National Register data in which a total of 325 PhD scientists identified with acoustics.

Description of Program Elements

1. The field of noise and noise abatement is a huge one in modern technology. It covers the sounds from jet engines, sonic boom, airflows in ducts and cooling systems, unwanted sounds of all kinds in housing and working areas. Closely related are the vibrations and shocks produced by machines. The program element has a considerable overlap with the program element of turbulence in fluid dynamics and has a strong interest in the problems of fluctuation theory. In both of these areas, physics has a role to play, but the relative importance of physics research to the entire field is small, and the share of physics research will probably remain similarly small. There is still need, however, for fundamental research on the way in which particular noises arise and on their transmission through various media.

2. The study of sound propagation in water, and more specifically, seawater, has been enormously stimulated by military needs. Most of the work supported in underwater sound has been technology rather than physics. There is strong overlap between this program element and that of oceanography. In rating both this field and that of noise, this overlap should be kept clearly in mind. Underwater sound will continue to play a significant role in the development of the field of oceanography.

3. Music includes studies of the character of musical sounds and how they are produced, both naturally and synthetically. Architectural acoustical studies are aimed at elucidating the factors that govern the acoustical character of concert halls and other structures, determining how these factors are related and how this knowledge can be translated into the design and construction of enclosures of specified acoustical characteristics.

4. The study of ultrasonic propagation in gases and liquids has long been a major component of physical acoustics. To traditional fluids, one should add the study of sound propagation in quantum liquids and in plasma. The use of Brillouin scattering to extend the frequency range of study upward, the prosecution of studies in liquid helium and plasma, and the application of our knowledge to border areas in chemistry and oceanography make this part of acoustics an especially lively one today. Of major interest has also been the contribution of this research to our understanding of relaxational phenomena and chemical

kinetics. The study of sound propagation in solids is usually classified elsewhere than in acoustics. Of more purely acoustical interest in studies of physics in solids are high-accuracy velocity change measurements. Spin waves and acoustic nuclear magnetic resonance and electron paramagnetic resonance have also been studied widely. The field of nonlinear acoustics has grown out of ultrasonic propagation studies in fluids and has high promise of applications in underwater sound and biophysical acoustics. Infrasound sources include volcanos, aerodynamic turbulence, weather frontal systems and tidal waves, and studies related to the large-scale behavior of the atmosphere, with application to clear-air turbulence detection and storm and tsunami tracking systems in this growing field of physical acoustics.

5. Represents the range of use in electrical and electronic techniques for devices that are acoustical in character and include modern stereophonic systems, acoustic pulse generation and detection, much of signal processing, and the use of computers in acoustics. The degree of involvement of physics with electroacoustics varies from time to time and depends on the particular stage of development of the devices and applications. Today, the most promising areas, from a physical viewpoint, are those of the direct production of ultrasound from electromagnetic radiation on a metal, the emission of acoustic radiation from dislocation walls in crystals, the use of heat pulses as sources of acoustic waves in the 10^{11} – 10^{12} Hz range, and acoustic thermometry. Many of these instrumentation studies are pioneering, and there is a substantial possibility of major advances in the production and use of sound.

6. While most of speech and hearing lie outside of physics, there is much that remains within it, such as models for speech production and analysis of the acoustic content of speech, and the mechanism by which hearing takes place beyond the conversion of mechanical motions of the inner ear to nerve impulses, as well as the nonlinear behavior of the ear and its effect on hearing. Since all of hearing and speech can be classified as bioacoustics, it is convenient to particularize the rest of the field by the term "biophysical acoustics," a field that goes beyond medical diagnosis and therapy. Biophysical acoustics overlaps with acoustic holography and includes the problem of communication of the deaf. Much of its basic thrust is in the development of ultrasonography, and the use of sound waves and acoustic devices in medical treatment. As physics, the field is still small; but it is of growing significance, and the future potential is large.

PLASMA AND FLUIDS (1970)

PROGRAM ELEMENTS	ESTIMATED FEDERAL SUPPORT (\$ Millions) ¹	ESTIMATED PhD MANPOWER ²
1. MHD power generation	1.0	20
2. Controlled fusion	30.0	410
3. Fluid dynamics, plasmas, and lasers.	20.7	425
4. Meteorology	7.3	180
5. Computer modeling		
6. Oceanography		
7. Laboratory and astrophysical plasma and fluids	0.4	10
8. Turbulence in fluid dynamics	2.6	65

¹ Approximately 55 percent of the scientists in plasmas and fluids are theorists. Annual support/PhD theorist is assumed to be \$40,000.

² Based on estimated level of activity and 1970 National Register data in which 1110 PhD scientists identified with plasma and fluids.

Description of Program Elements

1. It is possible using an intermediate state between plasmas and fluids, namely, a very-high-temperature conducting gas, to extract useful power by the flow of such a gas through a very strong magnetic field. The high-temperature gas may be the product of combustion, in which case, a very much higher temperature of combustion can and may be used as the initial starting state of a power-generating cycle. The feasibility of higher temperature in an MHD channel as compared with the limits imposed by boilers and turbine blades affords a possible significantly higher efficiency in power generation from the same fuel input, and, as a consequence, using MHD as a "topping" cycle affords the possibility of a significant improvement in the efficiency and simplicity of generating electrical power.

2. The goal of achieving useful power from controlled thermonuclear fusion of the heavy hydrogen isotopes requires the detailed and exhaustive understanding of the properties of high-temperature collisionless plasmas confined by various geometries of magnetic field. The thermal isolation afforded by various magnetic-field configurations is limited by a complex hierarchy of instabilities whereby the high-temperature fusion plasma can escape and cool at the walls of the vessel. The understanding of these phenomena toward the solution of the applied goal represents the most advanced application and understanding of plasmas and of the physics of plasmas.

3. Fluid dynamics, plasmas, and lasers include the basic physical understanding of the properties of plasmas and fluids and the application of this knowledge. Because of its separate importance, turbulence has been excluded but lasers mentioned to emphasize applications. An understanding of plasmas and fluids requires the very broadest knowledge of cooperative phenomena based upon principles derived from the simplest individual particle interactions.

4. Meteorology is a specific branch of the physics of fluids because of the complexity of the water vapor, water, air, rotational centrifugal field, and gravitational field of the earth-atmosphere system. Computer modeling, statistics,

observation, and weather modification are the ingredients for understanding the earth's atmosphere.

5. Computer modeling of both fluids and plasmas has progressed to the state where the most complicated flow patterns, convection partial turbulence, waves, instabilities, and plasmas can now be modeled using finite difference calculations on the more advanced computers. It is fair to state that the most advanced computer designs have, to a large extent, been motivated by the complexity of the modeling of fluid and plasma problems, particularly those associated with weapons design. In the future, we expect to see the problems of controlled fusion, meteorology, and oceanography have an equal and dramatic bearing upon the evolution of computer complexity.

6. The fluid flow of the ocean is complicated by a similar set of constraints as is the atmosphere, namely, rotation, gravitational field, and density stratification. In the case of the ocean, the thermohaline instabilities and density gradients lead to fluid-flow problems of great complexity. Oceanography in the context of fluid dynamics attempts to understand the fluid flow in the oceans due to the constraining forces as well as density gradients that lead to such exotic phenomena as the gulf stream, tides, and ocean waves. Understanding the interaction of the ocean and the atmosphere is a major objective of the physics of fluids of the earth.

7. Laboratory and astrophysical plasmas and fluids include the basic physical understanding of the properties of plasmas and fluids aside from turbulence, e.g., laminar flow, diffusion, transport coefficients, radiation properties, masers, lasers, and the application of this knowledge to the understanding of astrophysical phenomena.

8. Turbulence in fluids describes that quasi-random behavior that occurs when a highly coordinated flow breaks up into a series of partially correlated random fluctuations. In general, the fluid is characterized by the property that it may be infinitely extended quasi-statically with no restoring force. In addition, fluid turbulence exists without restoring forces; however, the one-body force that is included in fluid turbulence is gravity.

ASTROPHYSICS AND RELATIVITY

PROGRAM ELEMENTS ¹	1970		PROPOSED 10-YEAR PROGRAM	
	ESTIMATED FEDERAL SUPPORT (\$ Millions) ²	ESTIMATED PhD MANPOWER ³	ANNUAL FEDERAL SUPPORT (\$ Millions)	PhD MANPOWER
1. Gamma-ray detectors in astronomy	0.5	5	1.5	10
2. Digitized imaging devices for optical astronomy	0.5	5	1.5	15
3. Infrared astronomy generally	1.0	20	3.0	60
4. Very large radio array	— ⁴	—	10.0 ⁶	75
5. Aperture synthesis for infrared astronomy	—	—	2.0	20
6. X-ray and gamma-ray observatory	— ⁵	—	40.0 ⁶	75
7. Gravitational radiation	0.3	5	1.0	10
8. Neutrino astronomy	0.3	5	1.0	10
9. Theoretical relativistic astrophysics	1.3	50	2.5	100
10. General relativity tests	0.8	10	4.0	20

¹ These program elements at present include only a small fraction of the total research activity in astrophysics and relativity. They identify areas of research that are ripe for exploration.

² Total annual federal support for A&R is estimated at \$60 million. The cost of space-based observations amounts to about 3/4 of the total federal support. Nonfederal support of the field is substantial.

³ The total number of PhD's working in all aspects of A&R is estimated at 300.

⁴ A very large array for which design studies are complete and funding is being sought.

⁵ The High Energy Astronomical Observatory in space proposed by NASA.

⁶ Construction costs are included and amortized over a 10-year period.

Description of Program Elements

1. Gamma-ray detectors of greatly improved sensitivity, particularly in the 0.5- to 30-Mev region, are essential for understanding the history of nucleosynthesis in the universe. Also needed are better means of detecting gamma rays (> 10 GeV) that may be present as a result of a variety of energetic processes in exploding objects.

2. Equipping all large telescopes with digitized imaging devices would greatly aid work in cosmology by speeding up observations by a substantial factor and by permitting electronic subtraction of atmospheric interference over a large dynamic range.

3. Infrared astronomy, still a young discipline, requires intensive development both in terms of conventional telescopes and the invention of new techniques to permit further exploration of such vast energy sources as radio galaxies and quasars.

4. There is now need for a very large radio array (~ 27 dishes) capable of achieving beam widths of the order of 1 sec of arc at centimeter wavelengths for

studying the details of nearby bright sources with precision and for detecting faint sources out to the limits of the observable universe in spite of the confusion imposed by many apparently brighter sources.

5. The technique for synthesizing a large aperture using small apertures, so successfully used in the radio range, is being tested in the infrared range using a system aimed at resolutions of 10^{-2} sec of arc or better in strong ir sources such as galactic nuclei. It is important to develop this technique to the ultimate extent possible, perhaps even to the limit imposed by the diameter of the earth (10^{-7} sec of arc).

6. Construction of a High Energy Observatory in space for x and gamma rays would permit orders-of-magnitude improvement in sensitivity, position determination, spectral resolution, and variability measurements. Because x and gamma rays are emitted in great quantities by objects such as pulsars and quasars, it is important to cosmology to determine whether the backgrounds of these radiations are intergalactic in origin or due to a large number of superimposed sources.

7. Recent experiments are yielding indications that gravitational radiation is emitted from astronomical sources. In view of the need to test the predictions of relativity and to identify the extreme conditions that must exist in any source capable of emitting such radiation, it is important to continue and refine such experiments.

8. The attempt to detect solar neutrinos is critically important because of its implication for the whole theory of stellar structure and evolution on which so much of astrophysics is based. It is necessary that attempts to detect solar neutrinos continue until decisive results are achieved.

9. Application of the equations of general relativity to astronomically observable objects is important to verify the correctness of the theory and clarify the basic processes that are occurring. As in all astrophysics, construction of theoretical models is the only way we have of interpreting the fragmentary information yielded by observations of relativistic objects. Therefore in any balanced program, it is essential to increase our activity in theoretical model building in proportion to observational research.

10. Experimental tests of general relativity within the solar system have not achieved an accuracy adequate to distinguish Einstein's theory from competing theories of relativity. The advanced techniques and technology now available should enable clarification of this situation.

PHYSICS IN CHEMISTRY (1968)

PROGRAM ELEMENTS	ESTIMATED FEDERAL AND NONFEDERAL SUPPORT (\$ Millions) ¹	ESTIMATED PhD SCIENTISTS IN THE PHYSICS-CHEMISTRY INTERFACE ²	
		Physicists	Chemists
1. Molecular structure and spectroscopy	60	520	650
2. Kinetics and molecular interactions	73	850	600
3. Condensed phases	64	460	825
4. Surfaces	28	290	275
5. Other	25	300	200
	250	2,420	2,550

¹ Funding for scientists in the physics-chemistry interface area comes from sources that traditionally support physics and sources that traditionally support chemistry. The federal physics-related funds have been largely included in the funding estimates for atomic, molecular, and electron physics and condensed-matter physics. No attempt was made to quantify the funding of chemistry in the United States. The average annual cost per PhD does not vary widely from program element to program element and is estimated to be \$50,000/PhD.

² Based on estimated level of activity, the 1968 National Scientific Registry, and information provided by the Data Panel of the Physics Survey Committee.

Description of Program Elements

1. Includes spectroscopy of any sort (when structural information is its aim), quantum-mechanical studies of molecular structure (whether they are the phenomenological studies common to microwave and magnetic resonance studies or *a priori* studies of electronic structure), and electronic structure of solids in the context of the physics-chemistry interface.

2. The aspects of chemical kinetics in general that are considered part of the physics-chemistry interface, rather than pure chemistry, tend to involve reactions in the gas phase at all energies but concern reactions in condensed phases primarily at high energies.

3. Includes some parts of solid-state physics and chemistry and large portions of amorphous phases and polymers. Includes structure and dynamical properties of polymers, mechanical and electrical properties of liquids, glasses, and liquid crystals, luminescence and photoconductive properties of amorphous phases and molecular crystals, and some efforts toward developing devices such as liquid and plastic scintillators and amorphous switching devices.

4. Includes heterogeneous catalysis, sorption and evaporation, high-vacuum techniques, and reactions on surfaces and gas-solid interactions such as channeling.

5. Miscellaneous unclassified areas of the chemistry-physics interface.

PHYSICS IN BIOLOGY (1971)

PROGRAM ELEMENTS

COSTS AND MANPOWER

1. Molecular bases for biophysical processes
2. Neural physiology
3. Radiation phenomena
4. Clinical medical physics
5. Thermodynamics, energy balance, and stability

The Panel found it impossible to attach manpower or funding figures to the individual elements. The number of PhD physicists doing basic research in these areas is estimated at 250

Description of Program Elements

1. A very broad category involving use of almost the entire arsenal of physics probes from x-ray crystallography through nuclear magnetic resonance and Mössbauer studies to nanosecond fluorimetry.
2. Typical of sophisticated areas of study of macromolecular aggregates. Involves major design of new measurement techniques, computer simulation of neural behavior, study of signal transmission characteristics, and the like. Latest work on small animals with few hundred brain cells has shown remarkable symmetries.
3. Effects of both low- and high-level radiation on biological systems—uv to high-energy heavy particles. Regeneration and repair mechanisms. Long-term effects on populations.
4. Acoustics—how to explain sensitivity of human ear; optics—mechanics of locomotion and skeletal motions, etc.
5. Basic questions of energy utilization and control in biological systems.

Appendix A: Contents of Physics in Perspective, Volume I

CHAPTER 1. ORIGIN, OBJECTIVES, AND ORGANIZATION

- Background of the Report
- Origin of the Survey Committee and Panels
- Organization of the Report

CHAPTER 2. RECOMMENDATIONS

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Appendix C:

Physics Survey—

A Charge

to the Survey Panels

The following are topics on which the Survey Committee requests input information from the Panels:

THE NATURE OF THE FIELD

It is vitally important that we communicate to our audiences some coherent presentation of what we believe physics is all about. Please help us in this by considering how best to present your field to (a) other physicists, (b) other scientists, (c) nonscientists. Particularly in the latter case it will be helpful to provide the Committee with what the Panel may well consider an oversimplified and overpopularized view—previous panels have erred in the opposite sense. Examples, illustrations, case history—and indeed some historical perspective generally—will be most helpful.

THE STATUS OF THE FIELD

(a) What have been the major developments (both in theory and experiment) during the past five years? If possible put these into context with reference to the status statements in the Pake Survey and Panel reports.

(b) What are the implications of these developments for the growth of the field during the next five years?

(c) What are specific examples of major changes or advances that these new developments afford? Can we do things now that were simply impossible before? Are there examples that could provide striking graphic treatment in our report?

(d) What are the present frontier areas of the field? How are these defined?

(e) Is the balance between experimental and theoretical activity in the field at a desirable level? If not, what are the Panel recommendations concerning an optimum balance and how it might be achieved?

INSTITUTIONS OF THE FIELD

(a) How is activity in this field now divided among the various types of research institutions, i.e., academic, national laboratory (e.g., Brookhaven), government laboratory (e.g., N.R.L.), industrial laboratory, etc.?

(b) What recommendations does the Panel have concerning this balance and its possible modification in the next five years? The next decade?

(c) In this field, what are the characteristic features of activity in the different institutions?

(d) What are the interactions between these institutions? Are there areas where this interaction could or should be improved? What are the effective barriers, if any, that may prevent ready communication between, or direct exchange of, personnel for example?

INTERACTION WITH OTHER AREAS OF PHYSICS

(a) Illustrating with specific examples wherever possible, what have been the outstanding examples of interaction between this and other fields of physics recognizing that this is almost always a two-way interaction?

(b) What are specific examples of techniques—either experimental or theoretical—that cut across field boundaries? Detailed studies of selected examples would be particularly useful.

INTERACTION WITH OTHER AREAS OF SCIENCES

Questions identical to those above seem appropriate again with stress on the desirability of specific examples and possible illustrative material. The most important interactions will, of course, vary with the field; areas such as chemistry, medicine, biological sciences, ecology are obvious candidates for consideration.

INTERACTION WITH TECHNOLOGY

Research and technology have long advanced through mutual stimulation. In this field, what are the outstanding examples of such interaction in recent years? Case studies are particularly useful here. Purely as an example that has been suggested, it might be useful to consider an essay covering a tour through a modern hospital, a chemical processing plant, a paper mill, or the like, noting in passing those techniques and instruments that have arisen from work in the field. Cooperative efforts with other Panels would seem profitable. The inverse should not be neglected; some emphasis on the great dependence of research progress on technological progress is clearly indicated.

The Data Panel will attempt to arrive at methods of quantifying some of the available information in this area—both within and outside of this country. Close collaboration with the Data Panel in identifying areas of particular importance and interest would be most helpful.

INTERACTION WITH INDUSTRY

(a) Illustrating, wherever possible, with *specific* examples, what have been the outstanding interactions between this field of physics and the industrial sector in the past five years?

(b) Can any of the recent developments in the field be extrapolated, at this time, as having such interaction in the near, or distant, future?

(c) What is the inverse situation? What impact have techniques, products, or people in the industrial sector had on this field?

(d) How can the interaction between this field and the industrial sector be made more effective?

(e) It has been suggested that the development of biotechnology represents the conversion of the last of the guilds into an industry. What contributions has this field made to this conversion?

(f) Succinct case studies would be very valuable here.

INTERACTION WITH SOCIETY

- (a) In what areas is the field already having major impact on questions of direct social importance?
- (b) What other areas are candidates for such interaction?
- (c) What aspects of training in this field are of particular importance for utilization in problems of broader social implication—which of these latter in particular?
- (d) What would be the Panel recommendations concerning broader utilization of present personnel and facilities on such problems? Examples of possible situations would be most helpful.
- (e) A few groups have already decided to devote some selected fraction of their effort to such activities. A discussion of such approaches would be helpful.
- (f) One of the major questions facing physics (and science generally) is that of educating the non-scientific public to its very real relevance—however defined—in a technological civilization. The Survey Committee would welcome suggestions, case histories, examples, and any material that would assist in its consideration of this question for physics generally, as well as more specifically within the context of the Panel's subfield.

RELATIONSHIP TO OTHER AREAS OF SOCIAL CONCERN

Traditionally physics has been recognized as being relevant to national defense, atomic energy, space, etc., and has enjoyed support from the corresponding federal agencies. Today our society is moving its center of concern to areas for which, at first sight, physics is less relevant: health, pollution, racial tension, etc. The new federal agencies organized to deal with such questions, such as NIH, HUD, DOT, accept much less, or no, responsibility for physics. How strong a case can be made for the relevance of your subfield to the achievement of the missions of these other agencies? In general, this will come through the help your field can give to technologies that will further these social ends: for example, the role of computers (and therefore solid-state physics) in automating hospital care. However, there may be other more direct imports of your field that do not go through technology.

CULTURAL ASPECTS OF PHYSICS

Knowledge of the physical universe has more than utilitarian value. Each advance in fundamental understanding becomes an indestructible asset of all educated men. It is not suggested that each Panel should provide an essay on the contributions of its field to human culture, but it would be helpful in developing a broad exposition of this aspect of physics to have suggestions or compelling examples related to your field. A rather obvious concrete example: we know how old the earth is; that knowledge came through physics. Examples less obvious, and especially examples of important questions that may be answered in the foreseeable future, would be welcome.

We would welcome assistance from the Panel in answering such questions as (a) How best do we bring out the cultural relevance of physics? (b) To what extent should our report develop the cultural arguments as a basic justification for continuing support of physics? (c) How can we best address ourselves to the resurgence of mysticism and of anti-intellectual and antiscience attitudes among students? Among the citizenry generally? (d) What is the role of physics in countering these developments?

RELATIONSHIP TO NATIONAL SECURITY ACTIVITIES

- (a) What role has the field played in national defense activities?
- (b) What future role is envisaged? How important is the field to these activities? Disarmament activities should be carefully considered in this context.
- (c) What have been the respective roles of the different institutions of physics in this area?
- (d) Again the Committee would welcome the assistance of the Panel in addressing the general questions relating to the overall interaction of physics in national security activities.

C3

TRAINING IN THE FIELD

(a) It is often implied that contemporary graduate and postdoctoral training is becoming so narrow that students have lost the traditional breadth of outlook and flexibility expected of a physicist. Is this situation true in this field? What can be done to improve the situation? What recommendations does the Panel have for modification of contemporary training programs?

(b) In what ways is this field of particular importance for physics education?

(c) Although clearly the question relates to all of physics, can the Panel provide relevant input to the Committee concerning (i) the adequacy of current secondary school training in physics and mathematics; (ii) the effectiveness of some of the more modern secondary school curricula, e.g., PSSC; (iii) the relative intellectual standing, at the secondary school level, of those students who choose to major in undergraduate physics? (There is a widespread element of folklore that suggests that physics no longer attracts the most intellectually gifted secondary students. Can this be supported or refuted? What is the significance of this statistic in whichever case emerges?)

(d) Again, although relating to all of physics rather than to this Panel specifically, the Committee would welcome input concerning such topics as (i) what has been accomplished in bridging the gap between physics and other disciplines at the undergraduate level? How successful have general science or interdisciplinary courses been for entering—for advanced—students? How can we better illustrate the fundamental impact of physics as an underlying discipline in many areas of undergraduate education? (ii) Are teaching materials adequate? Do presently used textbooks adequately reflect the contemporary structure of physics? (iii) How important a demand for trained physicists will teaching requirements represent at established university centers—at newer campuses—at the colleges?

(e) To what extent has obsolescence of training overtaken members of the field? What can be done about it?

(f) What effective mid-career training opportunities now exist in the field? What are the Panel recommendations in this area?

(g) How effective are existing summer school programs in meeting the need for continuing training and education in the field?

(h) How effective are conferences and symposia in the field as training mechanisms?

(i) What are the Panel recommendations concerning the number and character of such conferences and symposia now available in the field?

POSTDOCTORAL TRAINING

(a) What is the role of the postdoctoral appointment in the field? This will, of course, be different in the different institutions.

(b) What is the average duration of the postdoctoral appointment? How has this changed with time?

(c) What has been the distribution, by nationality, of postdoctoral people in the field, and what fraction of these have remained in the United States following their postdoctoral training? How has this changed with time?

(d) How has the leveling of funding affected the availability of postdoctoral appointments in the different institutions (e.g., industrial laboratories, national laboratories, government laboratories, universities)?

TRAINING IN APPLIED AREAS OF THE FIELD

(a) What are the applied areas that draw most heavily on this field?

(b) Does the supply of physicists in this field suffice to meet the demand in these areas?

(c) Is the current training adequate? Would modification of current training patterns be expected to open up significant new employment opportunities?

(d) It might be argued that there has been a significant failure in communication between prospective applied physics employers and the academic groups involved in the applied training. Is this true in this field? If so, how can it be improved?

(e) How is the applied work distributed with regard to the type of institutions involved?

MANPOWER PROJECTIONS

(a) What is the current population in the field, and how has this population developed since 1965 (as covered in the Pake reports) in (i) academic research, (ii) industrial research, (iii) government laboratory research, (iv) postdoctoral training, (v) graduate student training, (vi) other?

(b) During the same period what migration has occurred into—and out of—the field? What have been the major sources and recipients of this migration?

(c) In the light of current challenges in the field and/or new or anticipated facilities, what projected manpower needs can be expected in each of the above areas in the next five years—the next ten (recognizing that this latter is an extreme extrapolation at best and closely related to available funding)?

(d) The argument is often advanced that the shortage of jobs requires additional funding in the field. This is more frequently reversed in Washington to imply simply that there are too many physicists being trained. What is the situation in this field?

(e) To what extent is the claim of inadequate employment opportunities legitimate (i.e., to what extent does this simply reflect the fact that for perhaps the first time physicists are not able to obtain the job that they would find most attractive)? What fraction of current PhD graduates were unsuccessful in finding employment where they were in a position to utilize their broad physics training if not their immediate specialty training?

(f) Will adequate manpower be available to staff emerging institutions in the field? How can qualified staff be attracted to and retained by such institutions?

(g) Does this field have unique or special characteristics that recommend it for consideration by an emerging institution?

(h) With leveling funding it may well be impossible for new (and indeed old) institutions to span as broad a spectrum of fields of physics as has been traditional, and while regrettable from a training viewpoint further specialization may be required in any given institution. How feasible are joint activities in this field as compared to others in physics? What recommendations would the Panel have in this difficult area?

FACILITIES

(a) Existing Facilities

(i) What are the major facilities in the field, and how are they distributed as to type?

(ii) Are the existing facilities now being utilized to full capacity? If not, explain.

(iii) How are present facilities being utilized, i.e., are they shared by more than a single group, how are decisions made regarding the research scheduling?

(iv) What are the outstanding problems now faced in the use of existing facilities?

(v) Is the distribution of existing facilities adequate?

(vi) Is modernization of the existing facilities feasible? What is the estimated effective lifetime of typical existing facilities in the field?

(vii) What criteria should be applied in reaching decisions to close down existing facilities?

(viii) To what extent do such criteria differ in different institutions (e.g., a facility might have training potential in an academic environment when it has reached a stage of unacceptable obsolescence elsewhere)? Is relocation of facilities a viable suggestion under such conditions? There are clearly pitfalls of which the receiving institution should be aware. What are they in this field?

(b) New Facilities

(i) What new facilities will be required to exploit the potential of the field? What is the priority ordering of these facilities? Please support with detailed discussion.

(ii) To what extent could existing facilities now used by other areas of physics be adapted for frontier use in this field?

(iii) What are the panel recommendations regarding siting and operation of new facilities?

(iv) Within this field what is an optimum balance between large centralized facilities and smaller more widely distributed ones? Please discuss.

(v) What new developments, now on the horizon show promise of evolution as major facilities in the field? Is an estimate of the probable gestation period and possible cost now possible for each?

THE IMPACT OF COMPUTER TECHNIQUES ON THE FIELD

- (a) What have been the outstanding impacts of computer technology in this field?
- (b) Would larger and/or faster computers be of significant value? What would be the relative priority assigned to the higher costs that would be involved here as compared to other major capital needs of the field?
- (c) Has any particular scheme of utilization, i.e., small local computers, institutional computer centers, regional computer centers emerged as preferable in this field?
- (d) Do existing software and languages pose significant limitations in the field?
- (e) What estimate does the panel have for the present and projected utilization of computers in the field? Can a dollar level be attached to this?
- (f) What impact has the field had on computer technology?
- (g) Are there outstanding examples of studies that would simply have been impossible without sophisticated computer utilization? Specific examples would be most useful.

COST INCREASES

- (a) Selecting, say, ten instruments much used in the field spanning the cost range involved—how have the individual costs varied with time in the last decade?
- (b) How has the average (very crudely defined) overall cost of an experiment, typical of those at the frontier of the field at the time, varied with time in the last decade?
- (c) How have average postdoctoral and student training costs varied over the same interval? It would be advantageous to consider experimental and theoretical situations separately in this instance.
- (d) Illustrating with specific examples what would be a reasonable annual estimate of the cost escalation in the field reflecting increasing sophistication of the studies themselves? Reflecting aging of the institutional staff?
- (e) To what extent is progress in the field *really* dependent upon the availability of the most modern instrumentation? It has been suggested that in some fields the instrumentation has become over-sophisticated, over-flossy and that in at least some instances the Ferrari could be replaced by a Ford without undue restriction of the research quality and productivity. To what extent is this suggestion true in this field? To what extent can (and should) it be countered? Specific illustrations and examples would be extremely helpful here.

FUNDING LEVELS

- (a) What have been the actual funding levels *and* expenditure levels annually in the field since 1965? Compare these with the Pake Report projections. Insofar as possible separate academic, industrial, and governmental laboratory operations for consideration. In some instances the leveling off of federal funding has been counteracted, for a time at least, by infusions of institutional funds, so that actual expenditure levels have not tracked funding limitations. What information is available on such phenomena in this field?

FUNDING MECHANISMS

- (a) How has the available funding been distributed among these sources: federal (AEC, DOD, NSF, NASA, others), state, industrial, local (university contributions, etc.), foundations, and other sources?
- (b) How does the funding process actually work for each of the above sources? What are the relative distributions, advantages, disadvantages, etc. of grants and of contracts? What are the effective

differences between these two approaches? What improvements might be suggested?

(c) What is the relative importance of project and of institutional grants in this field?

(d) How are decisions reached concerning grant and contract applications? Please comment on the decision-making processes at the national level—for example, by administrators in the various federal agencies and by advisory committees to these agencies. Is the present practice satisfactory or would change be desirable? What are the Panel recommendations?

THE IMPACT OF LEVELING FUNDING

(a) Discuss in some detail, with specific illustrations, the overall impact of leveling funding on the field. The following subtopics might prove useful:

- (i) Utilization of current facilities
- (ii) Exploitation of new discoveries
- (iii) Employment of physicists
- (iv) Support of the young researcher
- (v) Alienation of young physicists
- (vi) Possible new approaches to training in the field
- (vii) The support of off-beat proposals. There is always a tendency, under limited funding conditions, to eschew risk or adventure, to bet on the sure thing.
- (viii) Long-range implications for the field generally.

(b) It is clear that level funding is not synonymous with level productivity. The Committee will welcome case histories, etc. to illustrate this general point.

(c) What are the relative advantages of expanding (or contracting) activities in this field by expanding (or contracting) the size of existing groups active in the field as opposed to proliferating (or reducing) the number of such groups?

FUNDING PROJECTIONS

In the past survey reports have generally made specific projections and recommendations which have very often been negated by large departures of the total budgets available from those on which the recommendations were based. To be responsive, our report must provide for a spectrum of possible situations; in doing so it must carefully spell out, in as detailed fashion as possible, both the short- and long-range consequences of funding at levels below those necessary for both orderly growth and exploitation of new developments in each of the fields of physics. Specific examples and case histories will be particularly effective in illustrating these consequences. With these points in mind

(a) What level of funding, quite apart from any current estimate of future funding, would be required to enable this field to realize its full potential during the next five years? The next ten years? How would it be distributed broadly over the subareas of the field—recognizing that detailed projections are, in many cases, impossible?

(b) Consider a spectrum of possibilities ranging downward in 10% increment from that developed above to a level some 10% below that currently in effect. At each step indicate as clearly as possible

- (i) What opportunities would be missed—what developments would not be exploited?
- (ii) What new facilities would necessarily be postponed or eliminated entirely from consideration?
- (iii) What programs or facilities would necessarily be phased out or closed down?
- (iv) What the impact would be on the manpower and employment situation?

(c) A detailed discussion of the basic issues that underlie the Panel's assignment of priorities within the field would be an essential component of the Panel report. It is essential that long-range implications be developed realistically; it is essential that we not predict greater catastrophic impact than can be clearly justified.

(d) Separate discussion of major new facilities—in order of priority—with careful discussion of the bases for the priority ordering and of the relative justifications will be particularly important.

(e) The question of laboratories, as distinct from facilities, will be appropriate in some fields. The need for and justification of such laboratories will require careful consideration. What are the recommended criteria for closing down an existing laboratory in this field? To what extent are the laboratories in the field adaptable to broader use and to alternate modes of support during periods of fiscal stringency?

(f) To what extent can the Panel assist in developing a balanced presentation of the overall impact on the continuity of physics (i.e., the faucet effect—it is not generally appreciated that the reemergence of funding after an indeterminate drought will not guarantee reemergence of a healthy physics—or science—community)? Can this be quantified in this field? Are there relevant examples or case histories?

(g) A clear statement of the basic fiscal assumptions underlying the Panel projections is essential. The Data Panel will provide basic information concerning inflation rates, etc., which should be used systematically by all Panels to permit later direct comparisons by the Committee.

PHYSICS DATA IN THE FIELD

(a) How effective is communication of scientific information in the field generally? Are there adequate review articles—conferences and conference proceedings? Are there too many of the latter?

(b) What is the role of the preprint in this field? Is the present system effective?

(c) How adequate are the present data compilation and dissemination mechanisms in this field?

(d) What are the Panel recommendations in this area? Are new approaches or mechanisms required? How can manpower, adequate both in quantity and quality, be integrated into the data compilation activities?

(e) What is the estimated cost involved?

(f) Quite apart from data communication and compilation within the field, (i) how effective is communication with related fields that may have need of your data, and (ii) how effective are your data formats and presentations for their use?

INTERNATIONAL ASPECTS

(a) Where does this field in the United States at the present time stand with respect to the same field abroad?

(b) How does U.S. activity in the field compare on a manpower or funding basis with that in the most active foreign countries? What are the relative growth rates? What are the major points of similarity or dissimilarity in the overall programs? What has been the significance of the different funding techniques and levels?

(c) What international cooperation now exists? What would be the direct and indirect benefits to the United States in expanding such cooperation in this field? Are there particular facilities that should be considered in this light?

(d) What problems now exist with regard to the implementation of foreign cooperation and exchanges? Have problems been encountered in the obtaining of requisite visas—of permission to travel freely across international boundaries—of access to national or governmental laboratories in this country or abroad?

(e) What is the situation vis à vis international cooperation in physics in the industrial sector? Are there outstanding difficulties in this area? How important is fostering of such cooperation in this field?

(f) To what extent does this field encompass well-defined national schools of thought (e.g., the Copenhagen School in quantum mechanics and nuclear physics)?

(g) What has been the impact of foreign work and foreign research centers on activity in this field in this country?

(h) How do developing countries attain critical mass in this field? Are there specific mechanisms in this area? Should there be?

(i) What international laboratories *should* be developed in this field? Upon what criteria should the establishment of such laboratories be based?

ILLUSTRATIVE MATERIAL FOR THE SURVEY REPORT

It will be particularly important that the Committee receive from each Panel a selection of illustrations and photographs carefully selected to highlight progress or particularly interesting vignettes in each field. It would be helpful if the Panels would address themselves to this request at an early stage of their deliberations. The members of the Data Panel will devote considerable effort to the development of new techniques for the presentation of statistical data and will cooperate closely with each of the subfield Panels.